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Review of Geologic Data Sources for Coastal Sediment Budgets

by Edward P. Meisburger
Coastal Engineering Research Center

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3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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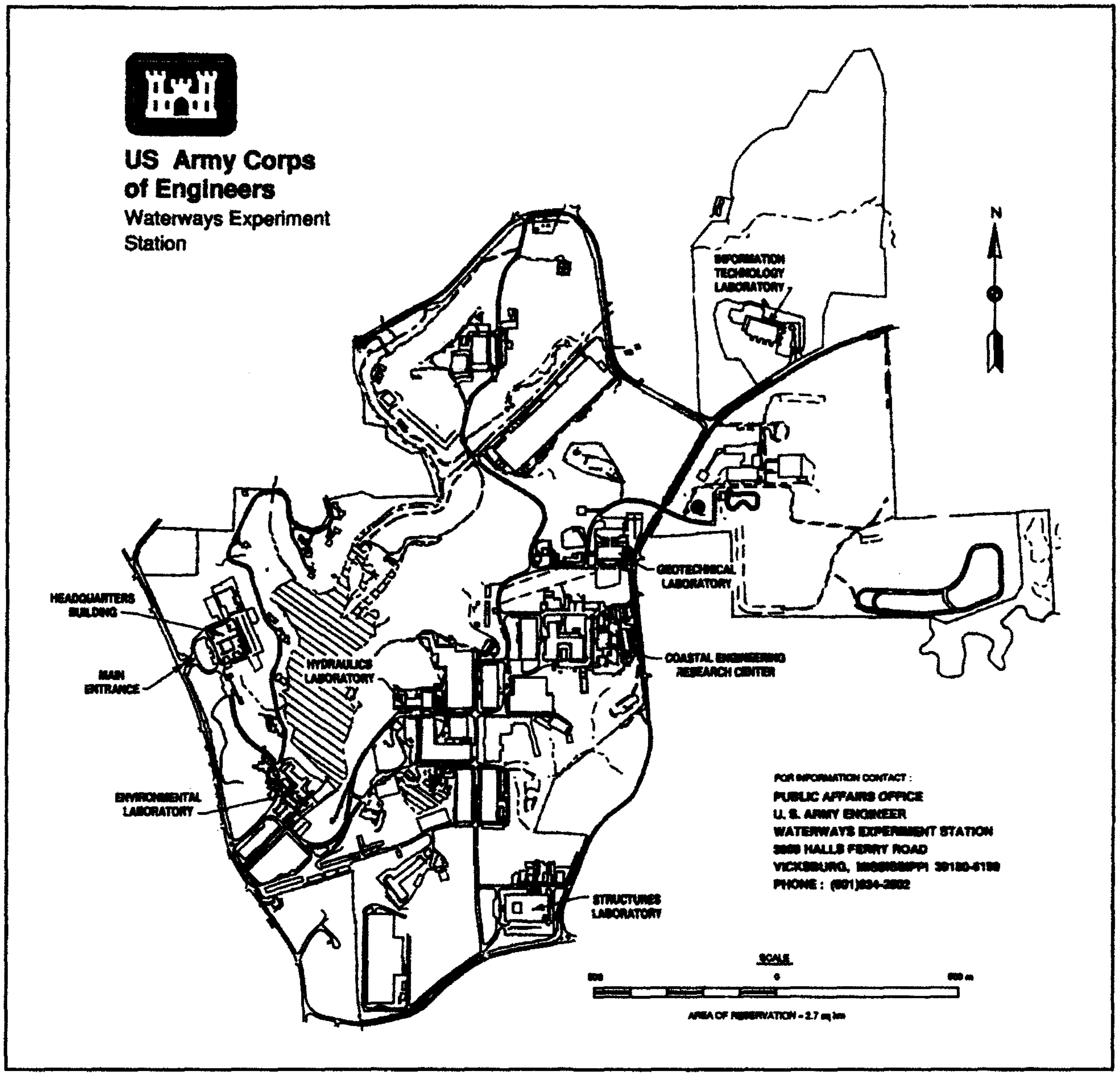

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Preface

The study reported herein results from research performed by the U.S. Army Engineer Waterways Experiment Station (WES) Coastal Engineering Research Center (CERC) under Survey of Technologies in Coastal Geology Work Unit 32538, Coastal Geology and Geotechnical Program, authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Mr. David A. Roellig was HQUSACE Technical Monitor. Ms. Carolyn Holmes is CERC Program Manager.

This report was prepared by Mr. Edward P. Meisburger, Coastal Geology Unit, Coastal Structures and Evaluation Branch (CSEB), Engineering Development Division (EDD), under the general supervision of Mr. Thomas W. Richardson, Chief, EDD, and Ms. Joan Pope, Chief, CSEB. Director of CERC during the investigation was Dr. James R. Houston, and Assistant Director was Mr. Charles C. Calhoun, Jr. The report was reviewed by Dr. Lyndell Z. Hales, WES Dredging Research Program, Mr. Andrew Morang, CSEB, and Dr. Douglas R. Levin, Bryant College, Smithfield, Rhode Island. Sections of the text were written by Mr. Morang.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

1 Introduction

Background

Sediment budget studies are used to determine the sources, sinks, and volumetric rates of sediment moving in or out of specific coastal compartments during a specified period of time. They are widely used in coastal, fluvial, and estuarine (wetland) environments. The proceedings of a recent conference on sediment budget techniques (Bordas and Walling 1988) contains 60 contributions. None were about coastal environments, but many techniques discussed were pertinent to coastal problems.

Coastal sediment budgets are calculated for specific coastal areas. The objective of a budget study is to account for the gain or loss of sediment through time by a study of the various factors that influence sediment erosion, transportation, and deposition in the study area. The measurement of many of these factors is exceedingly difficult, and most sediment budget studies do not account for all possible sediment sources and sinks in a given area. Thus, sediment budget studies vary widely in their reliability, and depend critically on the amount and accuracy of the basic data that go into them and the techniques of analysis used. In general, the reliability of sediment budget studies increases with (a) the length of time for which field observations and charts, maps, and aerial photography provide data for the pertinent environmental factors, (b) the number of factors for which some qualitative accounting can be made, and (c) the validity of subjective judgments that are usually a necessary part of the process at its present stage of development. This latter factor is particularly critical when analyzing old charts and maps and data that were collected in the field without thorough documentation of methods and instruments.

Natural trends and man-made environmental changes or structures are important factors in sediment budget analysis. Engineering design, construction decisions, and management plans affect, and are affected by, sediment budget considerations. For example, there is much concern that eustatic (worldwide) sea level rise has increased shore erosion and storm damage in many parts of the world and will cause even more severe problems in the future.

Sediment budget studies of specific coastal reaches have been made worldwide in connection with coastal engineering projects and studies of sediment supply. Because each area is unique in some respects, the techniques of sediment budget analysis will vary from study to study depending on the local environmental situation, available information resources, and the principal objectives of the study. Thus, having a set sequence of procedures for sediment budget studies is impractical, and sediment budgets are determined by the procedures and techniques most effective for the area under study.

Purpose and Scope of Report

The purpose of this report is to assess the geologic technology and methods available at present for performing the various elements of a sediment budget study. It is not intended to be a guide or manual for such studies, but rather to describe the techniques that have been developed and circumstances under which they are used, and to present deficiencies in present methods, which would be fruitful subjects of future research efforts. A recently published Engineer Manual, "Coastal Littoral Transport," contains detailed descriptions of how to calculate littoral transport (USACE 1992). This manual should be consulted by workers planning to develop sediment budgets for specific project sites.

Nomenclature

Nomenclature used by engineers and geologists to define features, zones, and boundaries in the coastal zone, for the most part, is not standardized. Many terms such as littoral, nearshore, inshore, and beach face have been defined in many different ways in the literature. For example, two important texts on coastal geology and engineering, and a widely accepted glossary of geology, define the term **littoral** in significantly different ways (Figure 1). *The Shore Protection Manual* (SPM 1984) describes the littoral zone as extending from "the shoreline to just beyond the seawardmost breakers." Komar (1976), in his *Beach Processes and Sedimentation* , describes the littoral zone as the "area between the inland limit of the beach to a water depth at which sediment is less actively moved." The American Geological Institute (AGI (1980)) *Glossary of Geology* describes the littoral zone as the zone "between high water and low water (Figure 1)." As a result of variable interpretations of the meaning of littoral in the literature, different sediment budgets of the same area can produce significantly different results if the boundaries of the littoral zone are not the same for each study. In this report, the definition of littoral zone is that proposed in Komar (1976). Another source of ambiguity is the division of sedimentary processes into sources and sinks in some studies and gains and losses (or synonymous terms) in others. The kinds of differences that occur can be seen in Tables 1 and 2, which

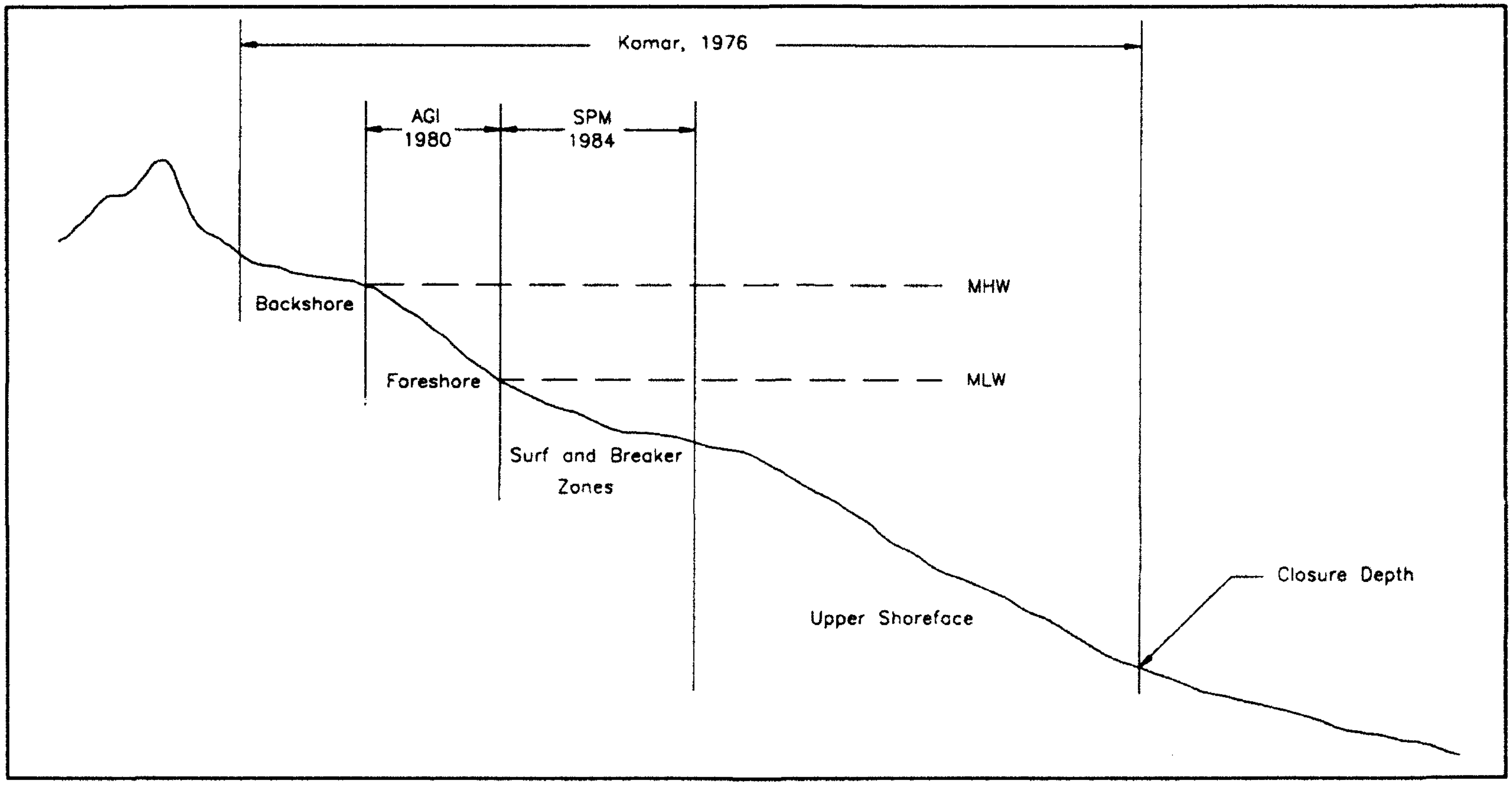


Figure 1. Limits of the littoral zone as conceived by three general references. Note that the AGI (1980) definition is entirely intertidal, the SPM (1984) definition is entirely subtidal, and the definition of Komar (1976) includes both the shore and the adjacent subtidal upper shoreface

Table 1
Classification of Sediment Budget Factors, *Shore Protection Manual* (1984)

Sources	Sinks	Both
Cliff erosion	Dune storage	Wind
Dune erosion	Backshore storage	Offshore slope
Backshore erosion	Inlets	Calcium carbonate, production loss
Beach nourishment	Lagoons	
Rivers	Overwash	
Longshore transport in offshore shoal or island	Mining Submarine canyons Dredging Longshore transport out	

Table 2
Classification of Sediment Budget Factors, Bowen and Inman (1966)

Credit	Debit	Balance
Longshore transport in	Longshore transport out	Beach deposition or erosion
River transport	Wind transport out	
Sea cliff erosion	Offshore transport	
Biogeneous deposition	Deposition in submarine canyons	
Hydrogeneous deposition		
Wind transport in Beach nourishment	Solution and abrasion Beach mining	

compare the subjects covered and the main categories as listed in *The Shore Protection Manual* (SPM 1984) and Bowen and Inman (1966). Because the differences in these tables can be a source of error, it is recommended that each study contain a table showing the factors considered and the classification of each factor in terms of its general effect on the sediment budget.

Sediment Budget Boundaries

Sediment budgets are made for specific areas that are defined by shore-normal and shore-parallel boundaries. These areas are often called sediment

budget compartments or, by multiplying the area times the depth of active sediment movement, sediment control volumes. Because the depth of the active sediment layer is variable in space and time, and is difficult to generalize, the idea of control volume is a useful concept but is difficult to establish in a quantitative sense. While arbitrary limits can be used for coastal compartments, it is most desirable that they correspond to some factors that are significant elements of the overall sedimentary environment. Boundaries can, for example, be delineated by headlands, submarine canyons, inlets, stream mouths, and divisions between eroding or accreting segments of shore. Because sediment budgets encompass the littoral zone, the different concepts of the shore-parallel boundaries already discussed make it imperative that the definition of littoral zone be specified in all sediment budget studies. Komar (1976) recommends that for geological studies the littoral zone should include the entire beach and the adjacent submerged zone out to the depth where sediment is less actively transported by surface waves. This is usually called the closure depth. The inland limit of the beach can usually be established on the basis of geomorphology or vegetation. The offshore limit, the closure depth, is more difficult to define in terms of how much movement of bottom sediments is significant.

The most direct and accurate method of defining a closure depth is accomplished using a time series of shore-normal profiles taken over a sufficient length of time to account for seasonal and longer term events that result in significant sediment movement (Figure 2). Ideally, a time series of a year or more is preferable. However, it is seldom possible to obtain sequential profiles over a long enough time period due to expense and insufficient lead time available for many projects. Hallermeier (1981) suggests that a reasonable estimate of the depth of significant sediment movement can be related to the nearshore storm wave height that is exceeded only 12 hr per year, and can be calculated by the following equation:

$$d_1 = 2.28\,H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \tag{1}$$

where

d_1 = depth of significant sediment movement (closure depth), ft, m
H_e = nearshore storm wave height exceeded for only 12 hr per year, ft, m
T_e^2 = associated wave period, sec
g = acceleration of gravity, ft/sec^2, m/sec^2

Based on a study of extensive field data, Birkemeier (1985) found that d_1 could be predicted with reasonable accuracy from H_e by

$$d_1 = 1.57\,H_e \tag{2}$$

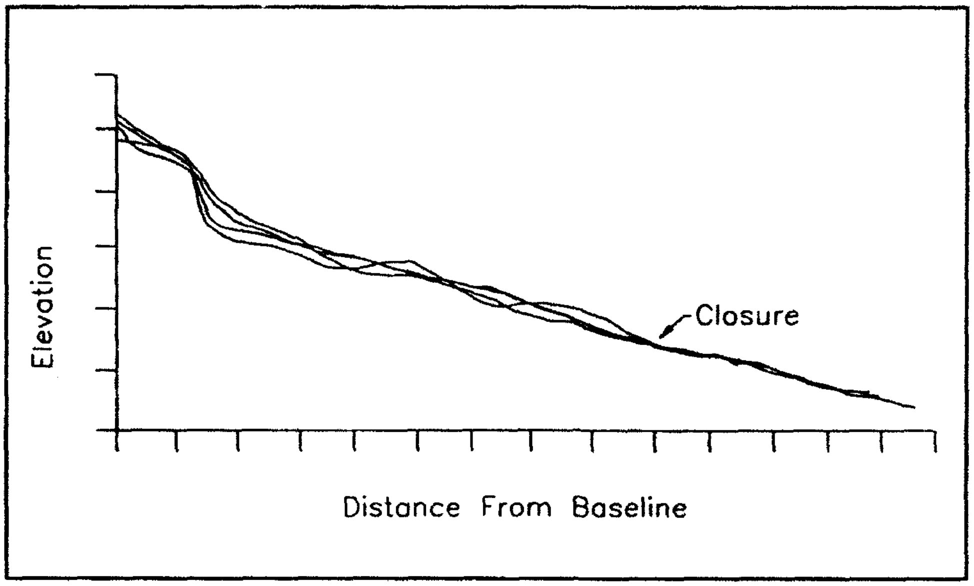


Figure 2. Repetitive littoral profiles. Note the closure depth at the point beyond which little profile change normally takes place

The equations above can be used to set the approximate offshore boundary of the littoral zone based on long-term wave data. However, to verify the results of the equations, a number of profiles should be monitored for at least a year if funding and time permit. The profiles also would provide some direct information on the volume of sediments being eroded or accreted throughout the littoral zone and on the reliability of an offshore boundary selected primarily by wave data analyses.

It is of great importance to include in any sediment budget study the criteria used by the investigator in defining the littoral zone of the area of study, and the factors that went into defining lateral compartment boundaries so that users can understand and evaluate the boundary selection.

2 Sediment Supply and Loss

General

A given littoral compartment may have one or more major sources of sediment supply. In some cases, the sources that contribute material to the active sediment mass of a compartment may be internally derived by substrate erosion, biological production, or recycling of sediments that have reentered the active mass after storage in inactive deposits. Some sediments may be only seasonally active or may be introduced by man as a result of farming or deforestation. Most sediments in littoral compartments are likely to be derived from remote sources and reach the littoral compartment by way of processes such as littoral drifting, stream discharge, and onshore transport of shelf material (Figure 3).

The littoral sedimentation system is dynamic where sediments are both gained and lost by various processes. In many cases, the gains and losses tend to balance out so that the amount of sediment in the compartment remains in a state of dynamic equilibrium. In other places, there is an imbalance between the amount of sediment gain or loss per unit time, resulting in accretion or net erosion within the compartment boundaries.

All sediment particles found along the coast have both an ultimate and immediate source. The ultimate source is the place where the particle originated and was detached from the parent rock, to become a sediment particle subject to transport away from the area of origin. The immediate source is the place from which sediment first entered the boundaries of the coastal compartment. In places where ancient rocks are exposed along a coast, the ultimate and immediate sources can be the same.

In addition to the ultimate and immediate sources, there are intermediate locations along the route of travel that have special importance to an understanding of the sediment supply system. An example of one of the intermediate stages where sediment particles may become trapped is a coastal plain unit that in some cases may last many millions of years. Changing geological conditions can cause renewed episodes of erosion and a resumption of coastward transport. While lying in intermediate deposits, the character of the material can be changed by chemical processes. These include leaching out of

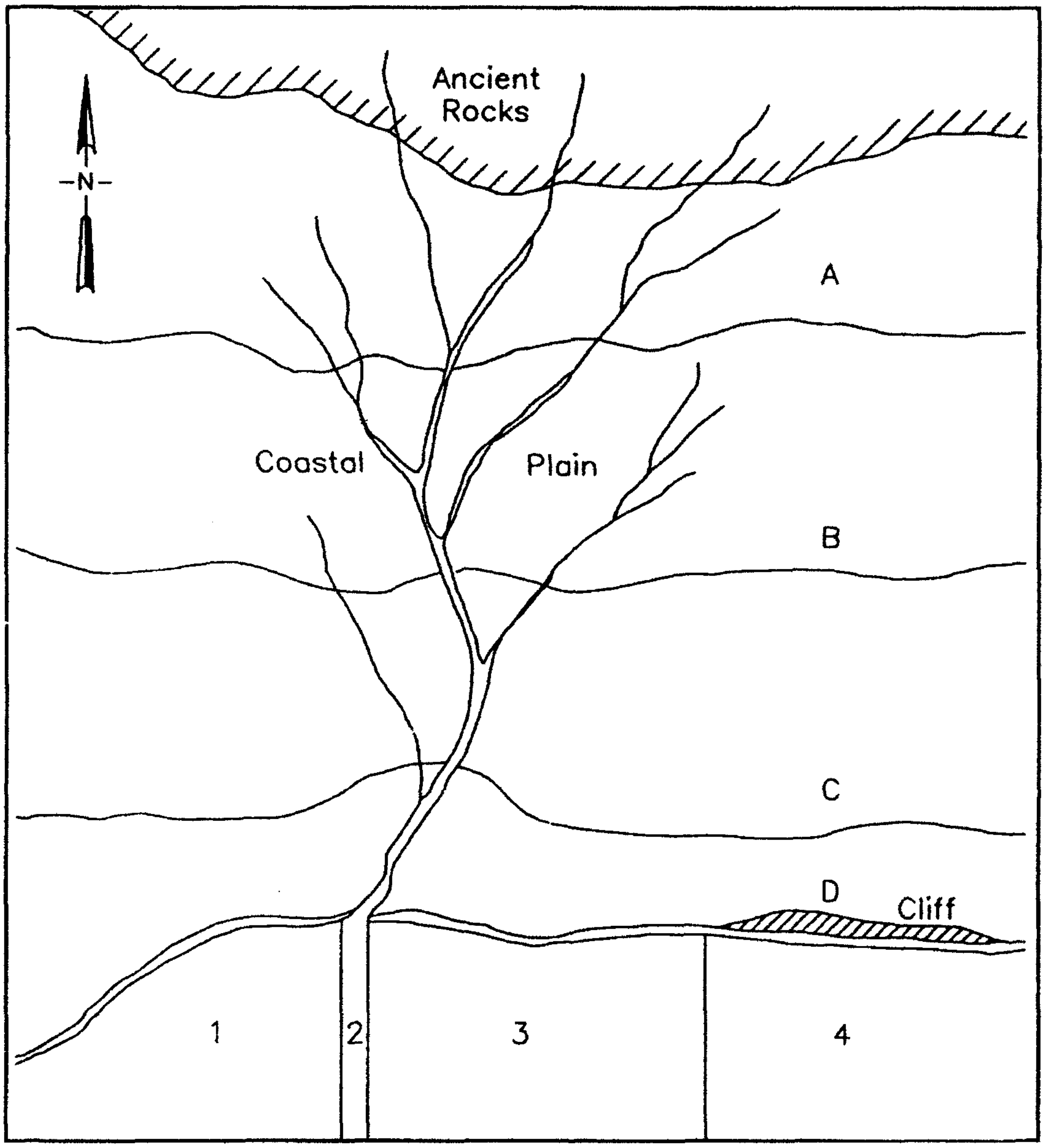


Figure 3. Schematic map of a coastal reach and hinterland showing subdivisions and potential source areas. The reach has been divided into four littoral compartments. The hinterland contains an upland area underlain by ancient rocks and four younger coastal plain units: A, B, C, and D. The headwaters of the stream drain the ancient rock area, which is the ultimate sediment source for the coastal plain units and modern coastal deposits. Some of the tributary streams arise in the coastal plain (intermediate sources). The cliff in compartment 4 is a potential immediate source, along with littoral drift across compartment boundaries, the stream mouth, and the off-lying seafloor

calcium carbonate and of less stable minerals such as hornblende. Chemical reactions with groundwater may also alter the mineral suite from that exhibited by the ultimate source rocks by addition of secondary materials such as pyrite or calcite.

An additional point of importance in studies of coastal sediments is the place in which a sediment particle first comes under the influence of the coastal sedimentation system. This interchange occurs most often at stream mouths, eroding headlands, and rock or sediment cliffs. The latter may represent the ultimate source or may have originally formed as sedimentary deposits from material transported to the area from an ultimate source or another intermediate deposit. A more detailed discussion of sources is presented in Chapter 4 of this document.

The following discusses the most important sources of sediment supply to the coast.

Fluvial Sediments

Streams are a major source of detrital sediments in coastal and oceanic environments. Much of the sediment discharged by streams may be in the form of silt and clay particles that are too fine to remain in the shore and shoreface area, and will eventually be deposited offshore in deeper water. In areas fronted by coastal barrier islands, spits, or baymouth barriers, much fine-grained material also can be deposited in the protected low-energy back-barrier lagoon, marsh, and tidal creek complexes. On the coasts of the Atlantic Ocean south of eastern Long Island and along the Gulf of Mexico coast, most streams have drowned lower courses forming estuaries in which sand-size sediment is often trapped, allowing only finer grained material to reach the open coast (Meade 1969). Tidal currents in many of the estuaries are effective in intercepting littoral drift sand from beaches and trapping it in complex estuary mouth shoals. Thus, the estuary acts as a sink rather than a source of littoral sand-size sediments.

The prevalence of estuaries on the Atlantic and Gulf coasts of the United States and in many other regions of the world is due to the relatively low elevation of coastal plains and recent eustatic (worldwide) sea level history. During the last large glacial event - in North America, the late Wisconsin glaciation - sea level dropped over 100 m below present elevation. The primary cause of the drop was the large amount of water trapped on land in vast continental and mountain glaciers. During the low elevation, streams flowed out across the present continental shelves, deepening the valley, and leaving behind deposits of sand-size material. As the Wisconsin glaciers began to wane about 18,000 years ago, a warmer epoch - the Holocene - which continues up to the modern day, was established. The warming trend caused melting of the continental glaciers and recovery of sea level to its present stand. The deepened lower courses of the seaward-flowing streams were drowned in this process and formed the estuaries that are now a conspicuous element of coastal geomorphology in many places.

On the Pacific coast of the United States, streams are important sources of sand-size and larger sediments. Though some estuaries occur, the predominantly highland coast and high-gradient rivers such as the Columbia bring abundant sand-size and larger sediment to the coast. The processes of coastward transport are highly episodic in many stream basins, especially where intermittent floods occur. The increased competence of streams during periods of flooding may account for the major sediment contribution in some places. The overall estimate of stream contribution to California's beaches is more than 70 percent, with the remainder of sediment derived largely from cliff erosion (Griggs 1987). In the Gulf and East coasts, sand supplied by rivers is also a major component of coastal sediments.

Quantitative measurements of stream-borne sediment are difficult to make. Data on rates of flow and measurements of suspended sediment load are obtained by the U.S. Geological Survey (USGS) and other agencies. However, there is little data available on the bed load sediments that generally account for the bulk of sand size and larger sediment particles, the sizes most likely to remain in the littoral zone. Usually, finer suspended load silt and clay are carried well offshore although the fine-grain materials may be trapped in estuaries and lagoons or may be deposited in coastal structures like cheniers. Some measurements of total sediment discharge can be obtained where reservoirs exist by measuring sediment accumulation in the reservoir for specified periods of time.

An indirect measure of stream-borne sediment transport rates can be made using geographical, climatic, and stream gaging information to compute the estimated sediment load by equations developed from theoretical and empirical sources. These equations relate measurable parameters such as basin area, precipitation, flow rate, and channel dimensions to sediment transport. Komar (1976) provides a discussion of the methodology of such calculations.

Cliff Erosion

Sea cliffs are common on highland coasts, but can also occur on some lowland coasts (Figure 4). Erosion of sea cliffs can be an important source of littoral sediments. The contribution of a given segment of cliff depends on a number of factors; cliff height, lithology, distance from the shoreline if fronted by a beach or wave-cut platform, wave climate, and biological and human activities.

One of the most important factors affecting cliff erosion is lithology. Erosion and sediment production related to cliffed segments of coast are usually very slow processes where the cliff is composed of consolidated rock. Jointed and thinly stratified rock in the ciiff face increases the erosion rate because water can more readily penetrate the rock face, resulting in frost wedging, chemical reactions, and lubrication of surfaces. Biological activity

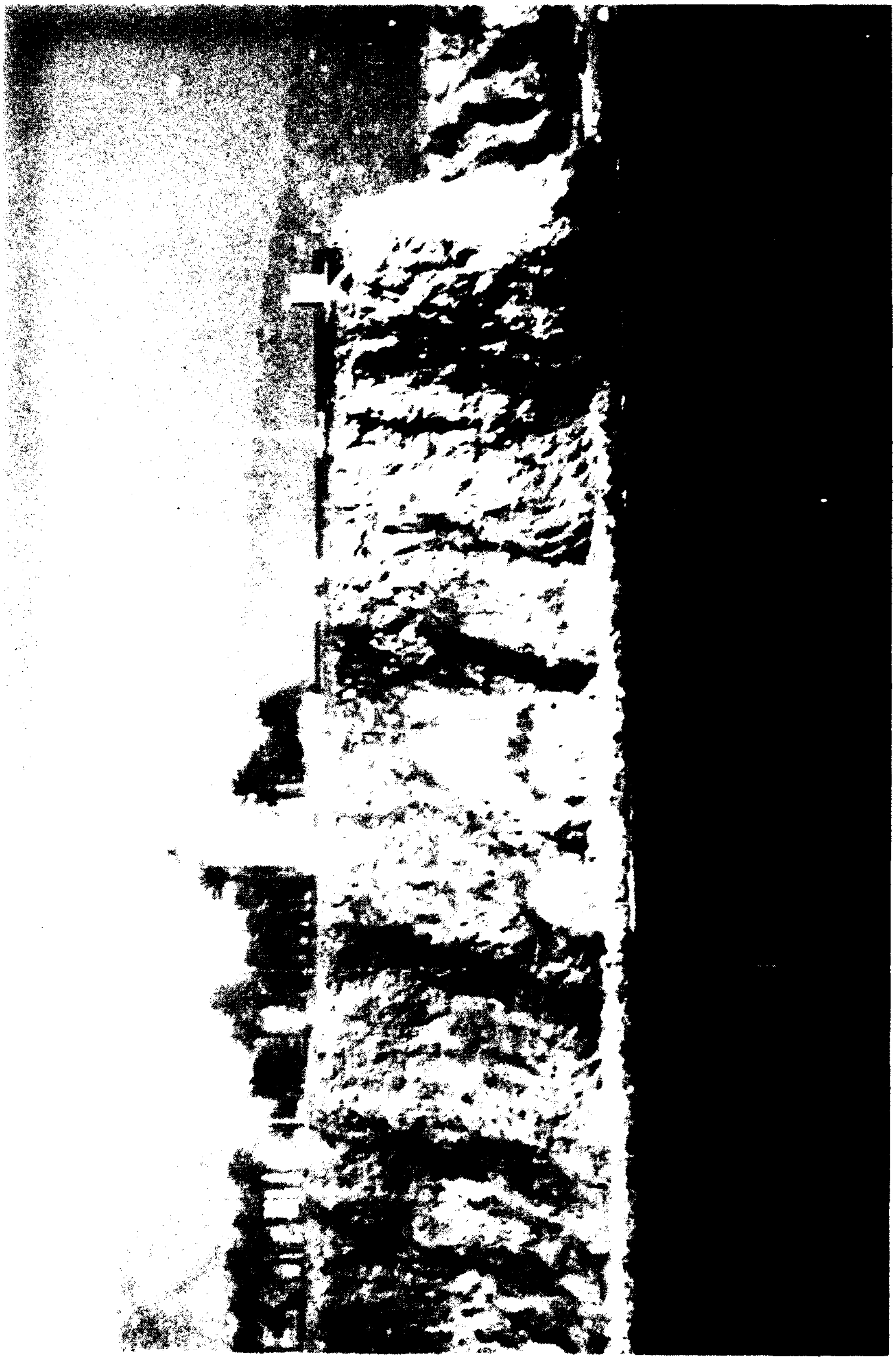


Figure 4. Typical sea cliff

in submerged or intertidal cliff faces can be effective in aiding erosion because many organisms are capable of boring into the rock, thus creating numerous holes that weaken the remaining rock mass. Among the more common rock-boring organisms are various species of mollusks, echinoids, algae, and sponges. In the upper cliffs, birds and hoofed animals like sheep contribute to erosion by making holes, eroding paths, and eating vegetation. On many rocky cliffs, pebble- and cobble-size fragments produced by erosion collect at the base or on wave cut platforms. There, they become effective tools in creating more fragments when the incoming waves repeatedly pick up and hurl them against the cliff face.

Many sea cliffs are composed of friable or unconsolidated material that is readily eroded by waves and is subject to slumping due to groundwater pressure and/or gravity. Many such cliffs are composed of silt- and clay-size particles that do not remain in the littoral zone but are eventually carried to deeper water offshore. Where coarser materials make up the cliff, there are generally a beach and shoreface fronting the cliff. A part of this material is likely to be transported alongshore to downdrift beaches where it is important in making up losses due to erosion. Beaches fronting cliffs may be wide enough to prevent direct wave attack of the cliff base most of the time. However, in severe storms, the cliff may be reached by the waves, but the cliff material that is eroded helps to replace storm-eroded beaches. As a result, a landward retreat of the cliff occurs. Use of structures such as seawalls, bulkheads, or riprap may reduce cliff erosion, but often at the expense of downdrift beaches, which receive some of their material from the cliff area by littoral drift.

Shore-Normal Sediment Movement

Movement of coastal sediments in an onshore-offshore direction is common. Much of this movement is within the onshore and offshore boundaries of the littoral zone and thus does not represent a gain or loss to the sediment budget compartment. However, gross movement in many places can be, and frequently is, much larger than net movement across the compartment boundaries. The most common example of large-scale movement that does not result in net loss or gain is the seasonal cycle in which the more severe wave climate of winter causes beach sediment to move offshore, where it usually accumulates in submarine bars. With the return of relatively fair weather and low waves in the summer, this material moves onshore and enlarges the beach. This cycle is especially seen in the U.S. West Coast (Bassom 1964). Net loss or gain from shore-normal transport occurs when large storms move sediment beyond the closure depth where it is not likely to return, or inland of the coastline. The latter can occur by wind transport of beach material, by wave washover, or in flood tidal shoal accumulation at inlets. Landward losses by eolian transport, overwash, and inlet-associated flood tidal currents are observable in the form of dunes, eolian flats, overwash

features, and flood tidal deltas, which can be monitored through time by use of charts, aerial photographs, and/or ground reconnaissance. In transgressive environments where barriers are retreating, dune, overwash, and flood tidal delta sediments may eventually be reexposed on the shoreface as the shoreline retreat progresses, therefore again becoming part of the littoral sediments. Recycled sediments are thus significant factors in projecting the future development of barrier islands.

The principal method of determining whether offshore losses or gains to coastal compartments have not been measured is by the detection of significant losses and gains that cannot be attributed to other factors. Essentially this is a process of elimination and presupposes that other possibilities have been accounted for. A good example of a study that led to inference of offshore sources is provided by Pierce (1969), and covers a long segment of barrier islands between Cape Hatteras, and Cape Lookout, North Carolina. Pierce (1969) found that after all known sources of sediment to the barriers were accounted for, there still remained a surplus of 441,000 cu yd (337,000 cu m) of sand per year that could only be coming from the offshore shelf because all other feasible sources had been eliminated.

Pilkey and Field (1972) considered that the proof of an offshore source should consist of (a) demonstrated surplus that cannot be accounted for based on sediment budget calculation, and (b) presence of unquestionable shelf-derived sediment components in the beach sand. Both criteria have rarely been met; however, this may be due to lack of investigation for natural tracers or lack of a unique natural tracer in the shelf sediments. In some studies where offshore samples were available, tracer elements have been found in the shelf sediments and on nearby beach and nearshore deposits (Pilkey and Field 1972; Peaver and Pilkey 1966; Laternauer and Pilkey 1967; Meisburger 1989; Williams and Meisburger 1987; Osborne, Yeh, and Lu 1991). Unfortunately, the attempt to find shelf elements in littoral sediments has not been a usual part of sediment budget studies but this type of investigation should be expanded in the effort to more completely account for sediment losses and gains.

If shelf elements are part of present littoral sediments in some locations, an important question arises as to whether or not this material is being provided at the present time or whether it reached the littoral zone sometime in the past when dynamic environmental factors were different. It has been suggested that during the Holocene Transgression, the rising sea drove a sediment wedge (probably in the form of a barrier island) before it into the presently existing littoral zone. Field and Duane (1976) and Pilkey and Field (1972) presented evidence that most barriers on the East coast were formed on the shelf during the last transgression and were driven landward until the sea level came to near stabilization, leaving the barriers in the approximate positions they now occupy. In this scenario, many modern shore and shoreface sediments were derived from the shelf under circumstances that no longer exist. This does not exclude the occurrence of onshore movement of shelf sediments at the present time as well (Dean 1987). Many sediment budget studies do seem to

indicate that, in places, substantial amounts may be coming from the shelf under prevailing conditions. Pilkey and Field (1972) found that oolites in beach sands of the Canaveral Peninsula area could only have been derived from the off-lying shelf. Many of the oolites in the beach deposits were found to be highly abraded, with the nuclear material exposed. They concluded that the oolites probably did not remain in the beach environment for very long without showing the effects of abrasion and that new material was probably coming ashore under present conditions.

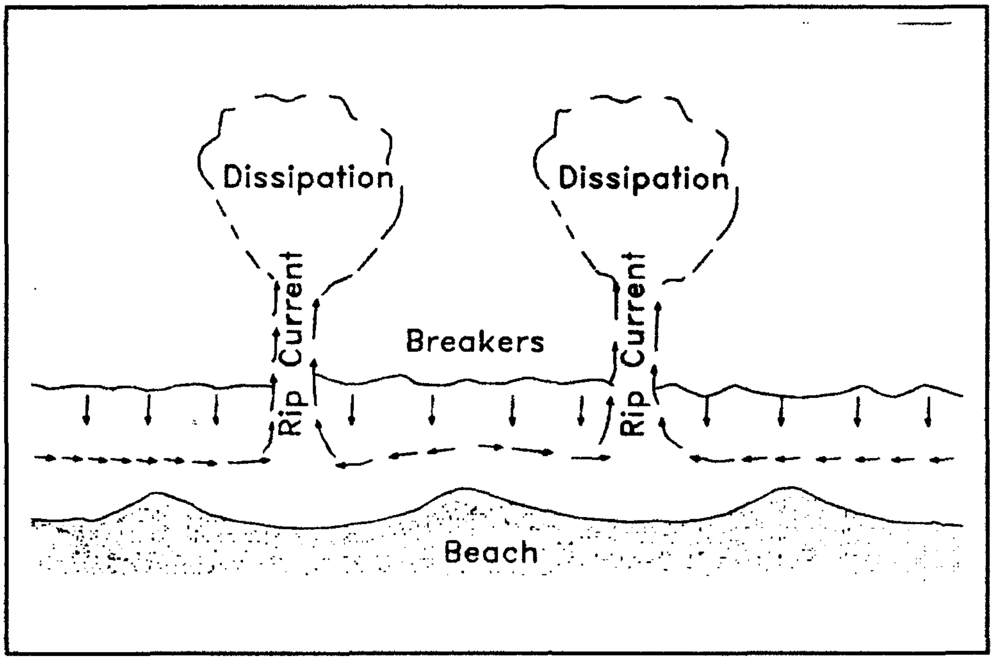
Longshore Transport

On coasts fringed by beaches, especially those that contain relatively long segments of open beach between littoral barriers, the principal transport process is likely to be longshore drift. Longshore drift is a shore-parallel movement of sediments created by waves breaking at an oblique angle to the shoreline. Two processes occur as a result of oblique waves impinging on the shore. One of these is beach drifting, which stems from the uprush of broken waves on the foreshore. The direction of the uprush of oblique waves is partly down-coast, while the backrush, under the influence of gravity only, is shore perpendicular. The particles in the uprush thus tend to move alongshore in a sawtooth pattern away from the direction of wave approach.

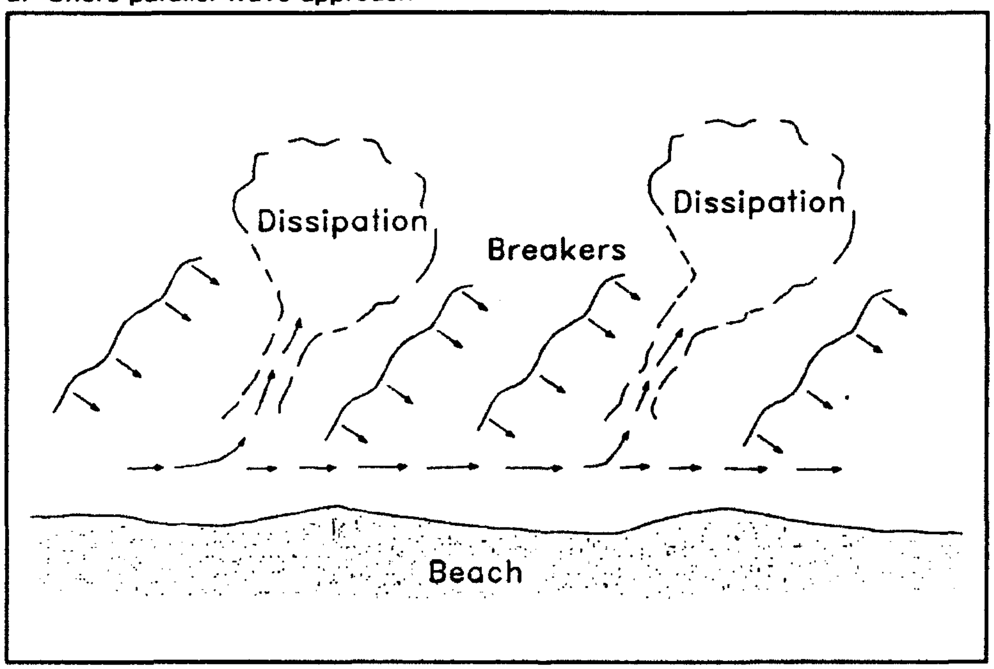
A second important mode of longshore drift is caused by shore parallel currents that are driven by the alongshore component of the wave energy flux. This current is confined largely to the zone between the shore and the outermost breakers. The effectiveness of the current transport is greatly enhanced by the turbulence created by breaking waves. The turbulence erodes sand from the bottom, placing it in suspension where it is more effectively moved by the current flow. Measurements of sand impoundment at littoral barriers show that longshore drift is one of the major factors in coastal sediment movement and enormous quantities of sand can be transported in this fashion. Many sediment budget studies are primarily based on longshore transport rates. The interruption of longshore sediment supply by structures or inlets is a frequent cause of downdrift sand starvation and consequent erosion problems (Figure 5). Thus, many coastal engineering projects are aimed at correcting an imbalance of alongshore transport by bypassing sand across littoral barriers or by adding sand from suitable borrow sources to the eroding beach at a sufficient rate to make up for the loss.

Under favorable circumstances, strong shore-normal currents appear from place to place along the shore. These are called rip currents and are well known because of their danger to swimmers and their ability to transport sediment seaward across the breaker and surf zones. Rip currents can occur in conjunction with both shore-normal and oblique wave approach (Figure 6). When rips occur during a period of shore-normal wave approach, the longshore and shore-normal currents set up a cell circulation in which

Figure 5. Effects of a jetty on littoral drift. The updrift beach shows the results of accretion due to entrapment of sand at the jetty. The downdrift beach has retreated and become thin due to sand starvation



a. Shore-parallel wave approach



b. Oblique wave approach

Figure 6. Schematic plan view of rip currents

relatively short longshore feeder currents flow toward the rip from either side (Figure 6a). Because of this, cell circulation does not create any net alongshore sediment movement. Oblique wave approach rip currents, if present, are fed from the longshore currents, which remain unidirectional, but fluctuate in strength because of the deflection of water at the rips (Figure 6b).

Littoral drift can both supply sand to and remove sand from littoral compartments. On the updrift boundary of the compartment, sand is being added, while often an unequal amount of sand is being lost across the downdrift boundary. The balance of littoral sediment losses and gains, however, must be determined by time series data because longshore drift reversals occur in many places, and net rather than gross transport rates are needed for sediment budget calculations.

Net littoral drift refers to the difference between the volume of material moving in one direction along the coast and that moving in the opposite direction (Bascom 1964). Along most coasts, the longshore currents change directions throughout the year. In some areas, the changes occur on cycles of a few days, while in others the cycles may be seasonal. Therefore, one difficulty in determining drift direction is defining a pertinent time frame. The net drift averaged over years or decades may conceal the fact that significant amounts of material also flow in the opposite direction. In addition, variations in meteorological conditions from year to year may result in changes in the net drift. For example, storms may cause large pulses of material to flow in one direction, while the fair weather drift may normally be in the opposite direction. Therefore, during especially stormy years, the net drift may be significantly different than during calmer years. Even subtle meteorological changes may cause great changes in the net drift.

The use of morphologic indicators can sometimes be the most dependable means of identifying the long-term drift direction in the coastal zone. Examples of various coastal environments and their interaction with longshore currents are summarized in Figure 7. In all the diagrams, predominant drift direction is from left to right, and land is in the upper part of the image.

a. A rocky headland has interrupted longshore drift by projecting farther seaward than the adjacent beaches. In addition, the wave field has probably been affected by refraction around the promentory. Sand has accumulated on the updrift (left) side of the headland, while the downdrift side is exposed and has suffered more erosion.

b. A sand spit is growing from left to right across the mouth of a stream or inlet where it enters the sea. Recurved beach ridges are formed as the spit grows. If the sediment supply is adequate, the spit may completely block the stream periodically. After heavy rainstorms, the stream may break through the spit at a location updrift of its previous opening. Warning: although the bend in the stream and the spit's projection to the right in this example normally indicate that drift is

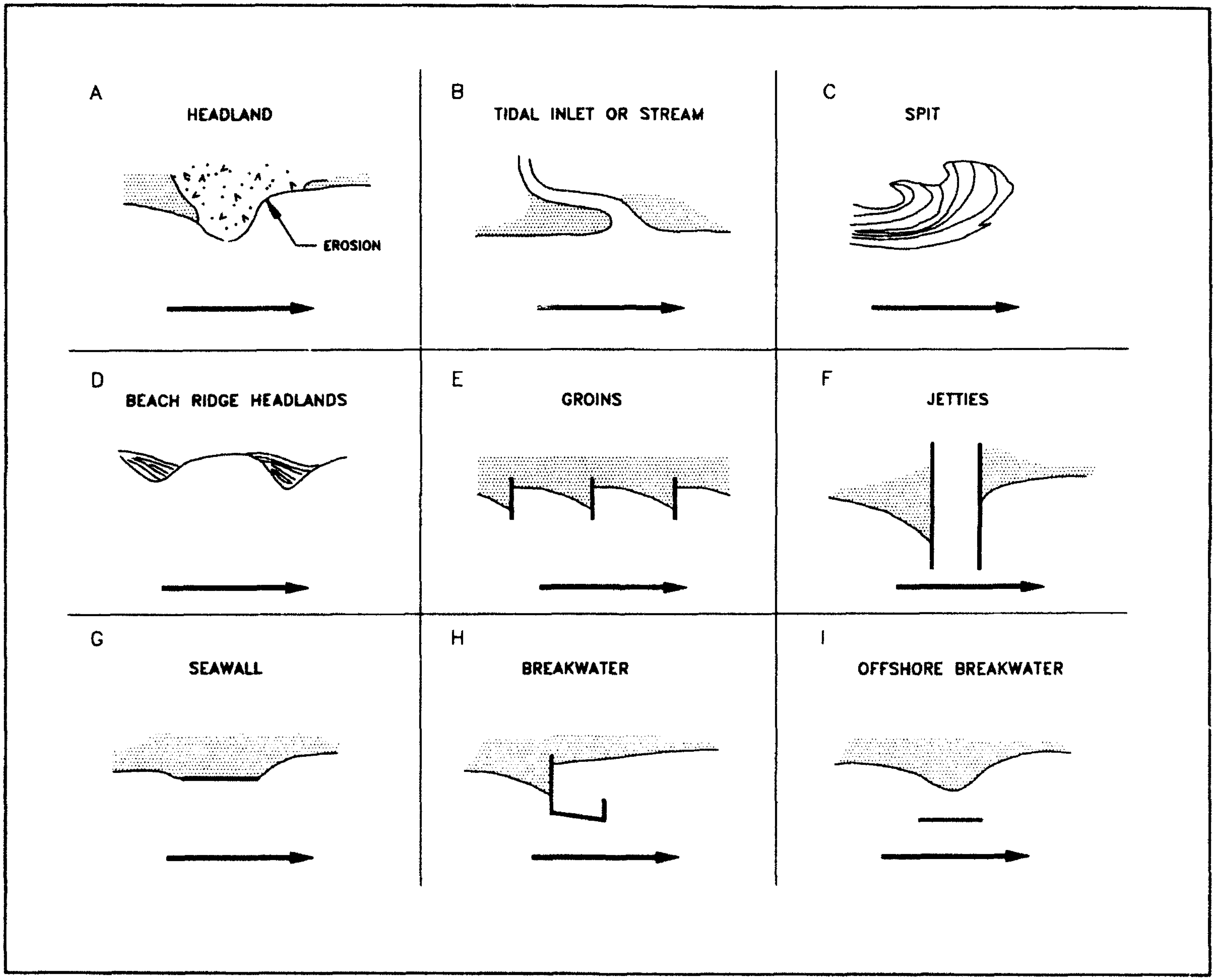


Figure 7. Morphological indicators of alongshore drift direction (descriptions of each diagram are in the text)

from left to right, there are locations where updrift inlet migration and spit growth have been documented.

c. The recurved ridges, which are convex to the right, and the convex shape of the entire spit indicate growth to the right.

d. Tapering beach ridges may represent locations where the boundaries of circulation cells have become well-established (Carter 1988). There may be only minor sediment transfer between cells. Transfer occurs when the ridge on the updrift end of a cell is eroded. The sand is then carried by littoral currents to the downdrift end of the cell, where it feeds the growth of more beach ridges.

e. Groins interrupt the longshore currents, trapping some of the drift. Sand accumulates on the updrift (left) side of each groin and erodes from the downdrift side.

f. Jetties, along with the currents which flow in and out of an inlet, interrupt the longshore drift. In this example, the updrift (left) side has prograded more than the opposite side. Accumulation on the right side suggests that occasional drift reversals may occur. Accumulation on the right may also be caused by local reversals which are caused by wave refraction over swash bars.

g. The seawall has protected a stretch of the shore and produced an effect similar to a headland. Although this part of the shore may be generally eroding, the shoreline loss is most pronounced on the downdrift (right) side of the structure.

h. An attached breakwater interrupts longshore drift similar to groins or jetties. Eventually, when the shore on the updrift side has prograded to the seaward end of the shore-perpendicular portion of the breakwater, sediment bypassing will be reinitiated. Shoaling within the harbor may become a problem then.

i. An offshore (detached) breakwater can effectively reduce longshore currents because a portion of the shore is protected from waves. As a result, the currents deposit their sediment load in the lee of the breakwater, allowing the shore to prograde. Downdrift, however, the shore erodes.

Biogenic Sediments

Biogenic sediment particles consist of the hard skeletal parts of marine plants and animals. Most biogenic particles are composed of quartz or calcium carbonate. Quartz particles are usually the remains of microorganisms such as diatoms that are quite small and fragile and do not often occur or remain intact in the beach environment. Calcium carbonate particles are derived largely from a diverse group of mollusks, barnacles, calcareous algae,

sponges, tube-building worms, corals, bryozoa, foraminifera, ostracods, and other organisms. Biogenic particles are found in most marine sediments but their volumetric importance varies widely as a function of biological productivity rate and terrigeneous sediment contributions. In the lower latitudes and in the deep ocean basins, some sedimentary deposits are composed wholly of biogenic material.

Biogenic sediment elements can be produced in situ or may be detrital elements transported from elsewhere. Transported biogenic material from a different environment or age can be of value in tracing sediment sources and movement. Common examples of biogenic elements occur on retreating barriers that are overriding their own back-barrier deposits. These deposits are then exposed to erosion on the seaward side of the barrier and become incorporated in the littoral sediments. By this process, many biogenic particles from organisms that live exclusively in back-barrier environments can appear in sediments on the open sea coast. Among the back-barrier fauna, the shell of the edible oyster *Crassostrea virginica* is often found on barrier beaches, as are less well known back-barrier species. On mainland coasts, cliff and substrate erosion can expose biogenic material from an earlier age that may consist of either extinct species or species found in different environments.

Biogenic material can be delicate, as are most of the quartz structures that come from diatoms and sponges. These are usually present in volumetrically insignificant amounts and are easily broken up in surf and beach environments. The calcium carbonate fraction of sediment contains elements of sufficient strength to withstand the environment of surf zone and beach for some time. Whole shells are usually broken into fragments as time passes and are continually exposed to abrasion by the harder components, becoming rounded and eventually being reduced to a size that is no longer retained in the littoral zone. However, production of new material probably is sufficient to maintain the percentage of shell material at a consistent long-term average.

In some tropical and subtropical areas, biogenic particles are numerous because of high production rates and may be the only component of coastal sediments in the absence of any terrigenous input. In many other places, they are a significant or major contributor to the volume of the sediment masses.

Artificial Beach Nourishment

Artificial beach nourishment is the process of placing sand on beach and dune areas to restore, maintain, or enlarge a given segment of shore. Artificial nourishment projects have been carried out on many shore areas with mixed results. Early projects often utilized sand fill that was too fine-grained to remain on the beach and was soon depleted by movement of the material offshore or alongshore at a rapid rate. Experience and research efforts have

led to better methods of selecting fill material with better stability characteristics, and better predictions of the timing and amount of maintenance nourishment that are needed on a periodic basis to replace losses.

Beach fill is less intrusive than structural protection and is generally preferable. However, in many cases, fill is supplemented by structures to prevent excessive loss of the material. Each fill project must be designed specifically for conditions of the project beach area. Suitable material must be found near enough to the project area for an economically feasible operation.

Both land and submarine borrow sources have been used for beach fill operations in the past. For relatively large projects, the submerged deposits have generally afforded a more economical and less intrusive means of operation. Guidance for offshore exploration to locate and define potential borrow sources is available in Meisburger (1990). In 1991, oolite aragonite sand was imported from the Bahamas to restore the beach on Fisher Island, Florida (Bodge 1992). The use of this oolite sand may be extended to other regions of Florida, particularly as readily accessible offshore borrow sites become depleted.

Inlets

An inlet is an opening connecting a bay or a lagoon with the sea. Of the many types of inlets, those that breach coastal barriers are the most often factored into sediment budget calculations. Many inlets are unstable, changing in size, location, and orientation through time. The opening and closing of inlets or their stabilization by jetties may have profound and lasting effects on sediment budgets.

Inlets along barrier coasts function mostly as sinks for littoral drift material. The drift, which is intercepted by tidal currents flowing in and out of inlets, is carried seaward or landward, where it accumulates in large inlet shoal complexes (Figure 8). Material carried landward during rising tide is deposited in a complex shoal known as the flood tidal delta, which is situated in the back-barrier area. As the tide falls, seaward-flowing ebb currents intercept littoral drift and carry it seaward to be deposited as the flow slackens in an ebb tidal delta. Ebb tidal deltas do not form everywhere. If wave energy is greater than tide energy, it is possible that an ebb delta will not form.

Where tidal inlets interrupt the free flow of alongshore drift, they reduce or virtually eliminate the supply of sediment to down-current beaches, causing sand starvation and often serious erosion problems. Thus, the creation of an inlet by man or nature can seriously affect the sediment budget of downdrift locales. Closure of an inlet can reactivate longshore drift previously trapped by the inlet, restoring to downdrift beaches the balance that existed prior to the opening of the inlet. A comparable effect has been achieved at some

Figure 8. Unstabilized inlet through a coastal barrier showing the presence of ebb and flood tidal shoals, Redfish Pass, FL

inlets by fixed or mobile sand bypassing plants that are capable of pumping littoral drift across the inlet where it can reach the downdrift shore. Although a certain portion of the drift can naturally bypass the inlet by means of the ebb tidal shoals, this is usually a slow process and often accounts for only a modest portion of the total drift.

Measurement of sediment trapped by inlets can be made by study of the growth of the tidal shoals. Also, where jetties or similar structures are used to prevent sand from getting into the inlet, measurements can be made of the growth of the updrift beach as sand builds up against the structure. Where bypassing systems are used, an accounting of the volumes of bypassed material is generally available by examination of records kept on plant operations.

Inlets can be sources as well as sinks, although it is probably rare that the character and amount of material supplied from back-barrier deposits is significant. In general, lagoonal and tidal creek sediments are fine-grained and, although these sediments can be carried to the sea by ebb currents, they are, for the most part, too fine to remain near the shore and are volumetrically insignificant.

Eolian Transport

Wind erodes and transports dry sand on the backshore and, at low tide, the dried foreshore. Wind ripples, thin heavy mineral crusts, and isolated pebbles and shells on sand pillars are indicative of this process. In coastal areas with predominantly onshore winds, sand eroded from the beach is carried inland unless blocked by cliffs or structures. Sand blown inland usually accumulates in coastal dunes behind the beach. Although this material is considered a loss in terms of the littoral sediment budget, dunes help protect inland areas from flooding and damage during storms. In addition, dunes are reservoirs of sand for the beach in the case of severe erosion. While efforts to reduce wind erosion of the beach are almost impossible to accomplish, measures are often undertaken to trap sand and promote dune growth and stability (Hotta, Kraus, and Horikawa 1991).

In view of the extensive dunes in some coastal areas, it is reasonable to conclude that wind erosion can be a significant factor in some sediment budget calculations. Estimation of the losses of beach material due to eolian transport is usually based on measurements of the growth of dunes by means of a series of aerial or ground surveys. The weakness of this method is that it does not account for offshore loss of sand. For example, in southern Louisiana on Isles Derniers, Hsu and Blanchard (1991) concluded that a net yearly loss of sand occurs because sand is blown to the southwest out over the Gulf of Mexico. Eolian transport also can be estimated using transport formulas and meteorological data. Horikawa, Hotta, and Kraus (1986) reviewed sand transport formulas.

It has often been hypothesized that inlets may be a sink for eolian sand on beaches where the winds blow parallel to the coast (for example, Long Island, New York). However, it is not known whether any field experiments have been conducted to verify this hypothesis and evaluate how important a factor it may be.

In most places, erosion of the beach by wind is a far more important factor than the addition of wind-transported material. There are undoubtedly locations where offshore winds produce a net increase of sand in the littoral zone (for example, the west coast of Africa where dust-laden winds blow off the Sahara). In most locations, however, the eolian contributions are probably modest and, in the context of the total sediment budget, may be of little significance. Nonetheless, eolian transport as a source must be considered as part of the process of calculating a complete sediment budget, although the mechanics of obtaining these data may be very difficult.

Overwash

Along many barrier shores, during severe storms it is common for waves to pass over the beach and penetrate the area inland of the coastline. In this way, material from the beach is carried inland and accumulates in the form of overwash deposits. A distinction between the process and the resultant deposits is sometimes made by calling the process "overwash" and the deposits "washover material" (AGI 1980).

On narrow barriers, washover deposits may extend into the back-barrier areas in the form of overwash fans. On narrow barriers, overwash deposits will eventually fill the lagoons. On wide, low-profile barriers, washover materials may not reach the lagoon and will accumulate on the normally subaerial beaches. The result of overwash on sediment distribution is to carry beach and littoral sediments inland of the coastline. Thus, there is a net loss to the littoral sediment mass as there is no direct process, except eolian transport, that can move any of the overwash material back. Frequent overwash and eolian transport can lead to retreat of an entire barrier. These transgressive barriers retreat landward across the overwash and back-barrier lagoon deposits (Figure 9). As the barrier retreats, the overwash zone also moves landward progressively.

Submarine Canyons

Submarine canyons occur mostly near the shelf edge and continental slope. In most parts of the United States, shelves are wide and submarine canyons are too far offshore to interfere with littoral transport. However, in places along the Pacific coast, the shelf is narrow and the heads of some of the many submarine canyons are close to shore. These canyons trap material moving as

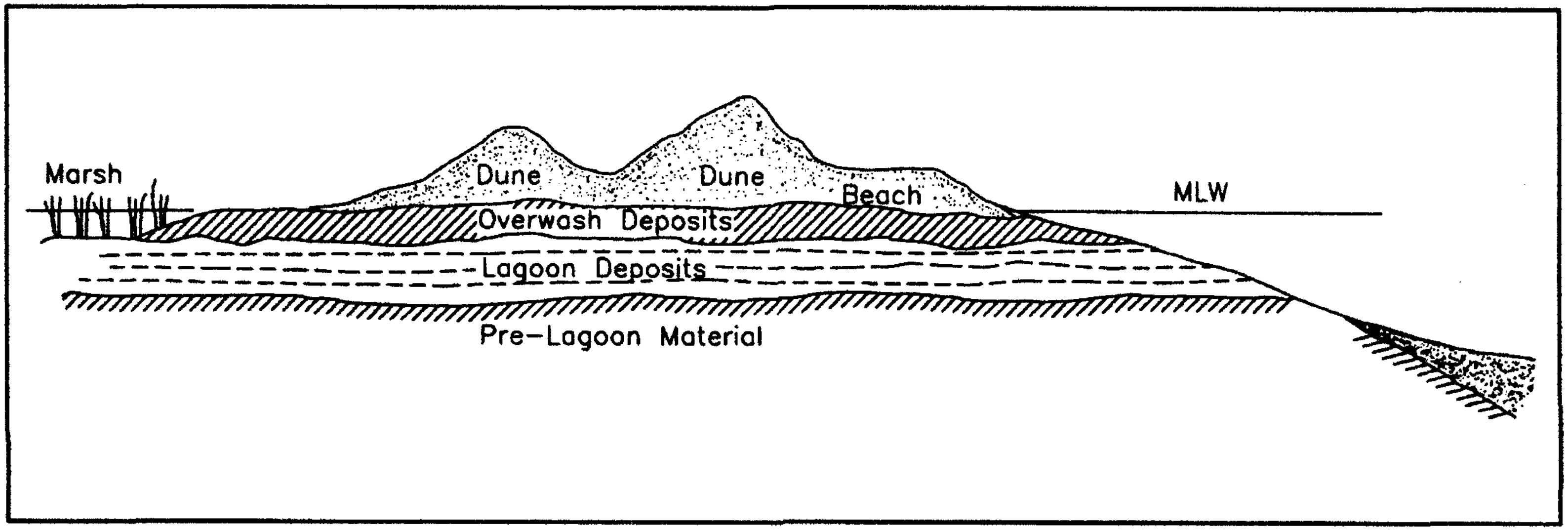


Figure 9. Cutaway view of a coastal barrier in the process of retreat across washover and back-barrier sediments

littoral drift (Shepard 1973, 1977). They permanently remove sediment from the coastal area because the materials work their way down to ever deeper water, where they may be transported to deep sea deltas. Thus, entrapment by submarine canyons is always counted as a loss since no mechanism exists that will move sediments in these canyons back toward the shore.

Beach Mining

Beaches are potential sources of economic minerals, including sand and gravel. Although beach mining has taken place in the past, it is now generally recognized that the value of beaches and dunes for protection against storm damage, and as recreational and ecological resources, far outweighs any economic gain that could be obtained by mining operations.

3 Sediment Budget Analysis Techniques

Several techniques are used for calculating sediment budgets. The technique to be used for a particular project depends on a number of factors such as local conditions affecting sediment supply and loss, availability of existing data, financial resources, lead time, and the purpose of the analysis. Probably the most widely used technique is the estimation of littoral transport rates based on analysis of ocean weather charts to reconstruct daily wave conditions (hindcasting) in the study area during a given time period. Data on drift rates also can be obtained by monitoring a series of littoral profiles over a sufficient length of time, or measuring the accumulation of sediment at a littoral barrier or trap. Repetitive hydrographic and shoreline surveys are available for many areas and, for some parts of the United States, cover periods of up to 150 years. However, the usually long time gaps between surveys do not allow for the recording of seasonal variations and extreme events. Aerial photographs are a means of looking at changes in a beach through time, and coverage of some areas may exceed 50 years; however, the coverage is usually infrequent and generally contains no data on the submerged zone seaward of the shoreline.

Because of the great importance of sediment budget data to the planning, design and maintenance of coastal engineering works and the development of coastal management strategies, a considerable amount of study has been devoted to the improvement of data collection and interpretation practices.

Littoral Drift Studies

Littoral (or longshore) drift refers to the process of lateral movement of sediment along the shore. It also is commonly used to quantify the material that is moved by the processes. Longshore drift occurs on the foreshore of the beach and in the surf zone. Two major processes account for most longshore drift; beach drifting, and alongshore current flow. Both are primarily generated by waves that approach the shore at an oblique angle to the trend of the shoreline.

Studies of the accumulation of littoral drift at littoral barriers and traps indicate that probably the most common means by which sediment in a coastal compartment is gained and lost is by longshore movement across compartment boundaries. Not uncommonly, the rate of sediment crossing the updrift boundary is equivalent to the rate of sediment leaving the compartment across the downdrift boundary, although these rates are frequently unequal. The obstruction or interruption of this movement by the natural or manmade breaching of an inlet, or by construction of a partial or total barrier, radically changes this balance unless measures are taken to bypass such obstacles by artificial means (Dean and Walton 1975). These means can include sand bypassing plants or addition of more sand from an outside source along eroding beach segments (beach fill or renourishment).

The fact that there is a cause-and-effect relationship between weather parameters and wave generation, and between wave characteristics and littoral drift, has important implications for sediment budget studies. Because a comprehensive and long-term database of marine weather information is available for U.S. coasts, it is possible to determine deep-water wave characteristics for a given area that extend many decades back in time. These reveal seasonal changes, long-term trends, and extreme events of low frequency such as major hurricanes. These deepwater wave characteristics can be converted to nearshore waves that have been transformed mainly by interaction with the bottom as the water shoals. From nearshore wave parameters, the potential longshore transport rate can be calculated. Thus the eventual product of this series of calculations is a long-term summary of the rate and direction of littoral drift in a specific shore compartment.

Wave Data Resources

The Corps of Engineers has been implementing two programs designed to greatly increase the accuracy and geographic coverage of the long-term wave database for the coasts of the United States. With input from academic, state and other Federal agencies, some phases of the program have been in progress since 1977. The ultimate objective is to provide coastal engineers with the type, quality, and time range of wave data needed for sediment budget studies and for the planning and design of coastal engineering works such as structures, beach restoration and maintenance, dredging, and dredged material disposal (Hemsley and Brooks 1989). Collectively, these efforts are known as the Coastal Field Data Collection Program. It is divided into two main parts; the Wave Information Studies (WIS) and the Field Wave-Gaging Program (FWGP). The FWGP is based on collecting long-term data from wave gages situated in both deep- and shallow-water sites off the U.S. coasts. The WIS studies are based on numerical hindcasts from weather charts covering a 20-year period. They cover deep ocean, continental shelf, and shallow-water sites of the U.S. coasts, both oceanic and the Great Lakes. The material available from these programs is a significant database for sediment budget calculations.

Wave Information Studies (WIS)

The WIS data are compiled by the U.S. Army Engineer Waterways Experiment Station (WES), Coastai Engineering Research Center (CERC). At present the studies provide data on significant wave heights and periods, mean wave direction, and wave spectra for the 20-year period 1956-1975. This is a long enough period of time to establish the main characteristics of the wave climate. Tropical storms are not included in the summary data but are hindcast separately to detail these extreme events.

The WIS studies are carried out in three phases. Phase I consists of data for deepwater oceanic ·:ds set up to form grid lines covering 125 n.m. (220 km) per side for the Atlantic and Pacific Oceans, and a finer grid (30 n.m. (55 km) square) for the Gulf of Mexico. This database is derived from information on wind speed and direction, which was computed from gridded atmospheric pressure field data. Supplementary data come from synoptic weather maps produced by the National Weather Service and from extensive observations made from ships at sea.

Phase II of the WIS program uses more closely spaced stations with grid cells 30 n.m. (55 km) square generally located over the continental shelf. Phase II, therefore, has many more data points and covers shallower water than the Phase I reports of the Atlantic and Pacific Oceans. Phase III reports consist of transforming the Phase II data to 10-m depth stations spaced at 10-n.m. (18-km) intervals, taking into account the wave transformation that occurs due to interaction with the bottom as the waves advance into shallow water. Phases I, II, and III have been completed for the Atlantic and Pacific coasts. Phase II has been completed for the Gulf of Mexico and Phase I, on a station spacing comparable to Phase III, has been completed for the Great Lakes.

WIS data are available to potential users in three forms. Wave data summaries have been published for the analyses that are most frequently used. Each summarizes 20 years of 3-hr hindcasts or 58,440 items. A complete listing of WIS reports is provided in Table 3. A second way to distribute WIS data is incorporated in the Coastal Engineering Data Retrieval System (CEDRS) which replaces the Sea-State Engineering Analysis System (SEAS). CEDRS is designed to provide access to WIS data, and to various other data sets, in the personal computer (PC) environment. The CEDRS database is subdivided into regional areas generally corresponding to Corps of Engineers District boundaries. Each regional database resides on a large external hard disk attached to an IBM PC-AT class computer. Along with the WIS data, the CEDRS system includes other data sources listed in Table 4. Installation of CEDRS systems in all District offices has been underway since 1990, and is scheduled to be completed by December 1993. Finally, WIS data are transferred to the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). Data can be obtained from NCDC through their Customer Service office, Federal Building, Ashville, NC 28801, reference WIS data from Tape Deck 9787.

Table 3
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(Continued)

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Table 3 (Continued)

Atlantic, Pacific, and Gulf of Mexico Reports (Continued)

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(Continued)

Sheet 2 of 3

Table 3 (Concluded)

Great Lakes Reports (Continued)

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General Users Information

Hubertz, J. M. 1992 (June). "User's Guide to the Wave Information Studies (WIS) Wave Model, Version 2.0," WIS Report 27.

NOTE:
All reports listed above were published by and are available from the U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

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Table 4
Contents of CEDRS Regional Databases

CERC	Wave Information Study (WIS hindcasts for U.S. coastlines Atlantic Ocean - 20-year time series 1956-75 for 108 stations Pacific Ocean - 20-year time series 1956-75 for 60 stations Gulf of Mexico - 20-year time series 1956-75 for 51 stations Great Lakes - 32-year time series 1956-87 for 317 stations
NOAA	National Data Buoy Center (NDBC) stations for all U.S. coastlines ± 100 stations for period of 1978-1992
CERC	Littoral Environment Observation (LEO) System ± 200 stations for period of 1966-1992
CERC	Field Wave Gage Program (FWGP) Scripps California Coastal Data Information Program ± 38 stations for period of 1976-1992 Florida Coastal Data Network ± 15 stations for period of 1979-1991 Other CERC project measurement sites

Field Wave-Gaging Program (FWGP)

The Corps of Engineers established the FWGP in 1977. The program's purpose is to manage, coordinate, and support the acquisition of wave climatology data from gages off the coasts of the United States. The data are intended to be used for planning, designing, and operating coastal projects and coastal research. The goal will be accomplished through a combination of long-term measurements to directly establish wave statistics, and short-term measurements to calibrate and verify numerical transformation models and hindcasts. Oceanographic parameters that are being measured include:

- Directional waves
- Non-directional waves
- Tides or water levels
- Currents
- Winds and other meteorology

Depending on specific local needs, not all of the above parameters are being recorded at all stations.

Primary data for the program are collected at a number of deepwater sites that operate on a continuous basis. Some of the deepwater buoys, operated by NOAA's National Data Buoy Center, have been in operation since 1978.

Nearshore wave gages, both directional and non-directional, are being operated by CERC, Scripps Institute of Oceanography, University of Florida, and U.S. Army Engineer District, Alaska. Table 5 lists pertinent addresses that readers can contact to obtain details of geographic coverage, and information regarding how to use and order wave data. Figure 10 shows projected FWGP deployments through 1994. McGehee (1991) tabulates specifics of the existing and projected stations.

Shoreline Change Studies

The objective of shoreline change studies is to use long-term movements in shoreline position to detect trends in shoreline erosion and accretion. These changes may be caused by variations in sediment supply and changes in relative sea level. The principal sources of data for making shoreline change studies are historical maps, charts, and vertical aerial photographs covering a given study area and showing the shoreline position at the time of each survey or aerial photographic overflight. Conversion of a measured shoreline excursion to a volumetric gain or loss is made by use of a volumetric equivalent factor that relates the horizontal distance of the excursion to a volume change across the entire profile. The accuracy of this factor is vital to the reliability of the study and must be calculated with care.

Table 5
Sources of Data for the Field Wave-Gaging Program

Source	Type of Information
Coastal Engineering Information and Analysis Center USAEWES 3909 Halls Ferry Rd. Vicksburg, MS 39180-6199 (601) 634-2012	Coastal Engineering Mangement Information (CEMIS) System, gage data from the Corps Coastal Field Data Collection Program and other sources.
Alaska Coastal Data Collection Program Plan Formulation Section U.S. Army Engineer District, Alaska Pouch 898 Anchorage, AK 99506-0898 (907) 753-2620	Wind and wave data for coastal Alaska.
California Coastal Data Information Program Scripps Institute of Oceanography Mail Code A022 University of California, San Diego LaJolla, CA 92093 (619) 534-3033	United States west coast gage network and gage at CERC's FRF in North Carolina.
Field Coastal Data Network Coastal & Oceanographic Engineering Department 336 Weil Hall University of Florida Gainesville, FL 32611 (904) 392-1051	Coastal Florida wave gage network.
National Oceanographic Data Center User Service (Code OC21) 1825 Connecticut Ave., NW Washington, DC 20235 (202) 606-4549	Variety of oceanographic data including NDBC buoy data.

Historical maps and charts

In the United States, maps and hydrographic charts of all coastal areas have been compiled from direct surveys. In most cases, resurveys have been made to update the data. Consequently, a time series of shoreline changes between surveys can be obtained for most areas. Many of the original surveys were made more than 150 years ago, and upwards of six or seven resurveys have been made over the years. Thus, for many areas, a time series of shoreline positions over an extended period of time can be constructed by comparative analysis of the shorelines.

The richest source of historical map and chart data for the U.S. coasts is the National Ocean Service (NOS) of the NOAA. NOS archives contain copies of all NOS surveys as well as the survey data of their predecessor agency, the U.S. Coast and Geodetic Survey. Many of the earlier surveys, though made without the modern techniques and instruments, were rigorously

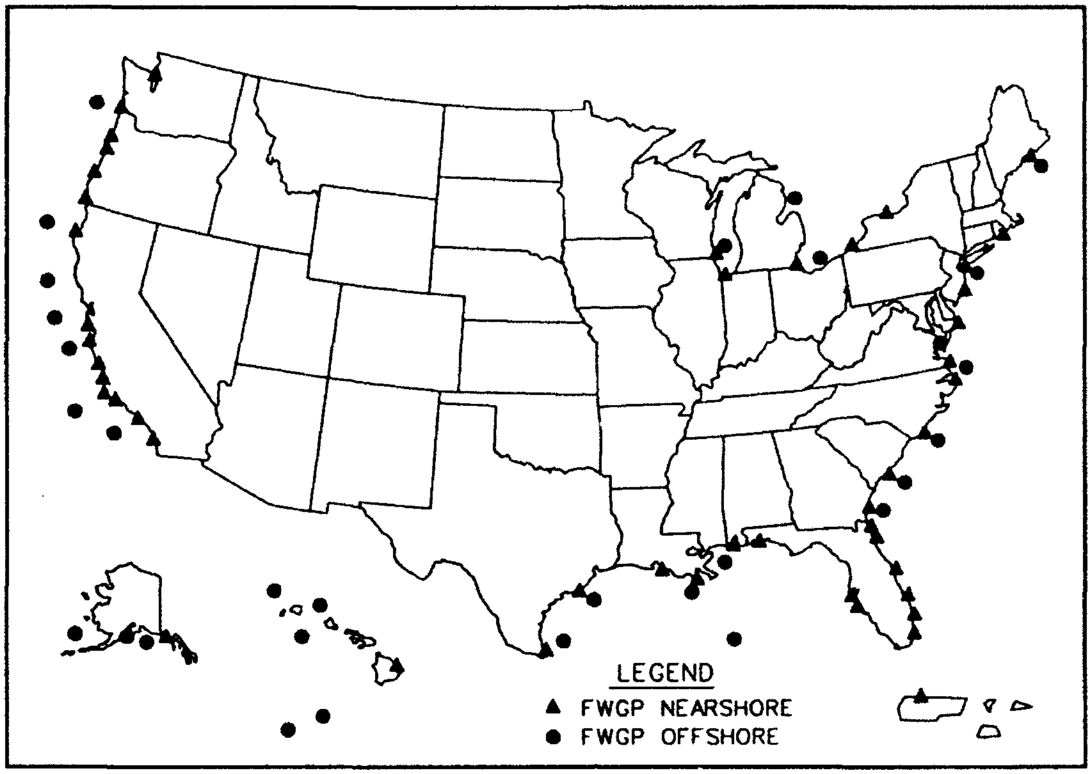

Figure 10. Field Wave Gaging Program projected deployments through FY 94

conducted and are reasonably accurate. Another useful source of map data is the USGS, which is responsible for mapping the land areas of the United States. Their maps of coastal areas can be obtained at a scale of 1:24,000 and show shoreline positions at the time of survey.

Maps and charts used for historical shoreline change studies should be at the largest scale available. For NOS surveys, in which published charts providing comprehensive coverage are at 1:80,000, it is expedient to use the preliminary sheets from which the charts were compiled, as these are of considerably larger scale. They are archived by NOS, and copies can be obtained on request.

For comparative study, shorelines from available surveys are adjusted to a common scale and delineated on a base map. Each shoreline is printed in a separate color or, if in black and white, identified by distinctive line symbols (e.g., solid, dashed, dot). Measurements of the distance between each succeeding shoreline position are made at frequent intervals to determine shoreline displacement. In some cases it will be found that the shoreline has moved landward; in others, seaward movement or relative stability is indicated. Overall, shoreline change maps may show a mix of periods of advance and retreat over all or part of the record. In many cases the movements may all be in the same direction, indicating long-term trends that will possibly be continued in the future and are thus valuable input for shore management and coastal engineering design studies.

Examples of shoreline change maps made in a cooperative program between NOS, CERC and the state of North Carolina are shown in Figures 11 and 12 (Anders, Reed, and Meisburger 1990). In Figure 11, the various shorelines shown in distinctive colors on the original are numbered for identification. In the 1-mile-long (1.8-km-long) compartment on Capers Island, South Carolina, shown in Figure 11, a shoreline advance occurred between the 1857 survey and the 1875 survey. This was followed by a consistent trend of retreat through all the later surveys up to the last in 1983. Overall retreat during this period was approximately 700 m. The retreat rate can be determined for successive inter-survey periods by dividing the retreat rate by the number of years between the surveys. Figure 12 shows a section of shore near Surfside Beach, South Carolina, that shows little shoreline change between the first survey in 1875 and the latest in 1983, in contrast to Capers Island. Although they cannot be separately distinguished in most places, there are actually six surveys shown. Even on the colored originals, the lines cannot be differentiated in most places. In contrast to the shore at Capers Island, the Surfside segment appears to have been reasonably stable for the 108-year period between the first and last surveys, and there is no indication of a trend.

Existing studies

Many Corps of Engineers coastal districts have prepared shoreline change maps in connection with shore protection and beach erosion studies. These maps can be obtained from District files. A cooperative study between NOS, CERC, and state agencies in recent years has provided shoreline maps on a regional scale for parts of the Atlantic coast. Two completed reports cover a segment between Cape Hatteras, North Carolina, and Cape Henry, Virginia (Everts, Battly, and Gibson 1983), and from Cape Fear, North Carolina, to Tybee Island, Georgia (Anders, Reed, and Meisburger 1990). Work is in progress on another report covering the Delmarva Peninsula from Cape Henlopen, Delaware, to Cape Charles, Virginia. Similar studies have been undertaken by the Florida Department of Natural Resources, by the NOS and USGS for the Great Lakes, and by the State of New Jersey for most of their coasts. The California shore was mapped as part of the Coast of California project (U.S. Army Engineer District, Los Angeles 1987).

Aerial photography

Aerial photography of U.S. coastal areas provides repeated overflights going back 50 years or more, and is thus very useful for shoreline change studies. Coverage is available from a number of Federal and state agencies, especially the USGS, the NOS, the U.S. Department of Defense, and the U.S. Department of Agriculture.

Measurement of successive shoreline positions on aerial photographs can be difficult because tidal and nontidal variations in water levels occur almost

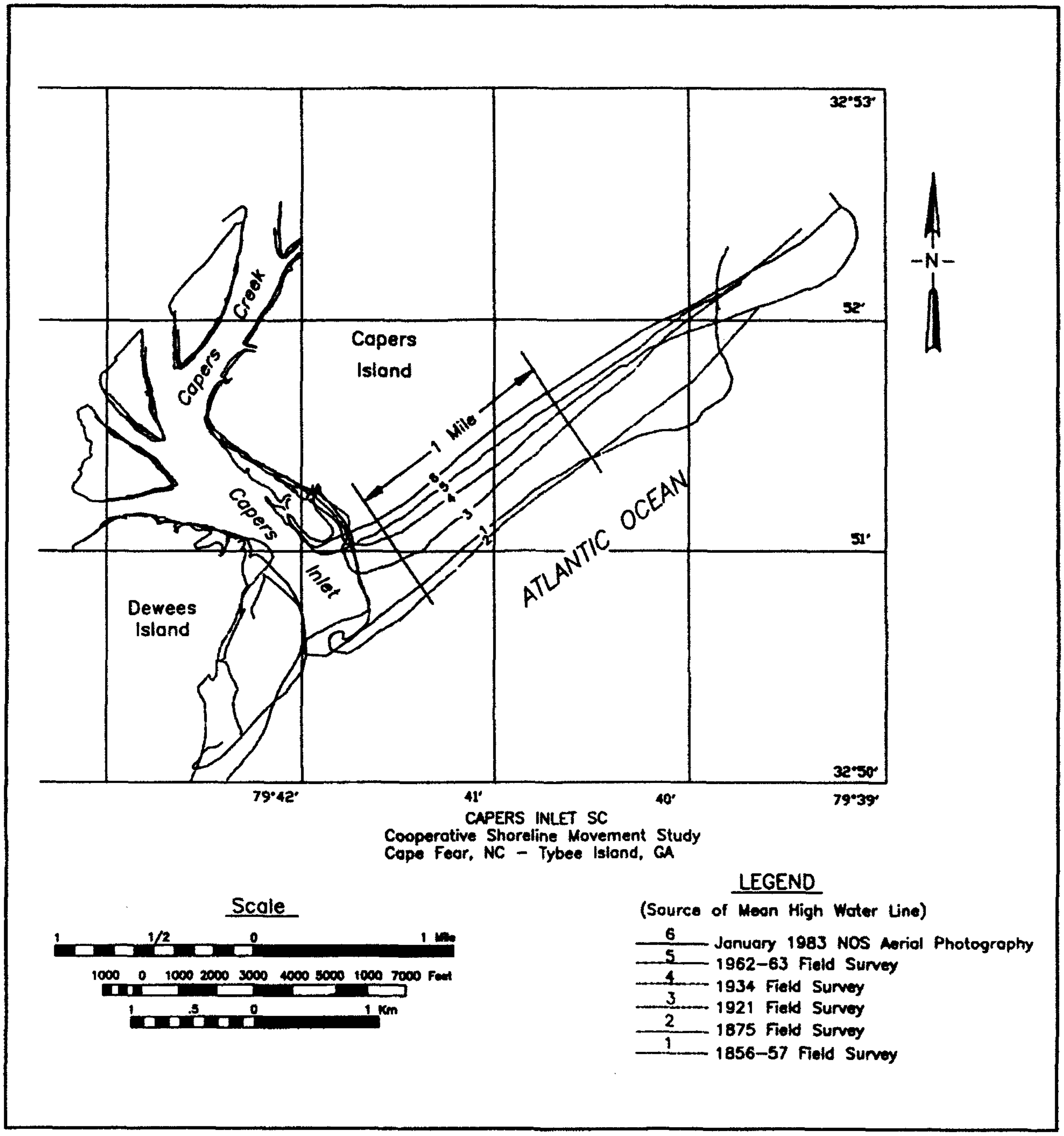

Figure 11. Shoreline positions at Capers Island, SC, during a period of 118 years showing a consistent retreat of the shoreline between the 1885 survey and the latest survey in 1983

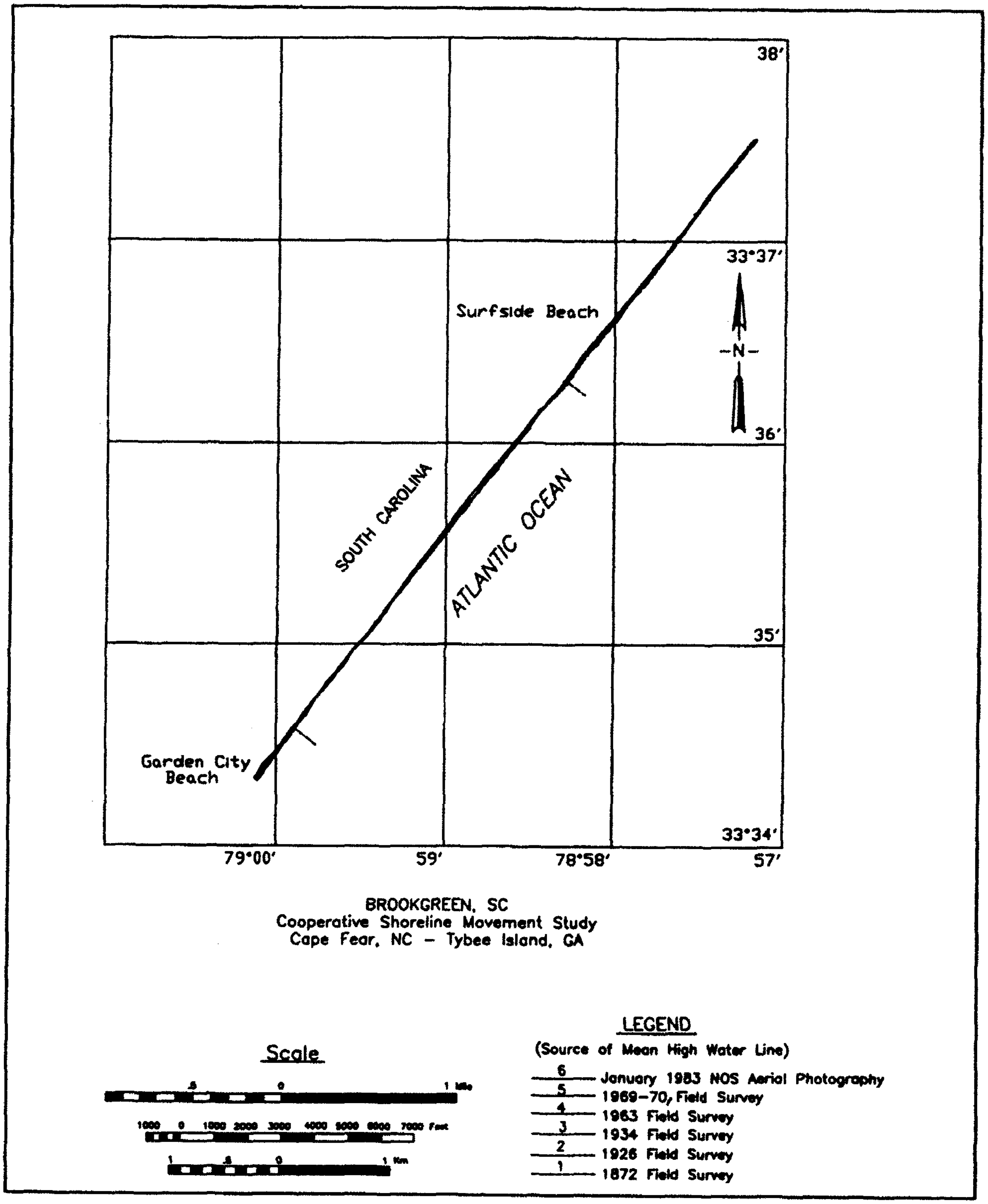

Figure 12. Shoreline positions at Surfside Beach, SC, showing little change over the past 111 years

continuously. Therefore, a well-defined shoreline position is needed to make comparison of time series practical. What is needed is some common reference line that can be located on photographs taken under varying tidal and wind surge conditions that will provide a common base for comparison of time series photos. Reynolds (1987) described a sediment budget study based entirely on aerial photographs spanning a 15-year period. As a common reference that would show erosion, accretion, or changes in relative sea level, he used the high water line. He describes this as the line marking the limit of uprush at high water, identifiable by a change in tone between the wet or moist sand seaward of the high-water line and the lighter shade of the dry backshore. Other examples of work in which this concept was used are cited by Reynolds (1987).

Volumetric conversion

The shoreline change method of identifying areal changes in beaches does not account for the volumetric change across the entire littoral profile that is associated with the advance or retreat of a shoreline. One method of accounting for this volumetric change is based on a "rule of thumb" stating that 1 ft (0.3 m) of shoreline advance or retreat is equivalent to the loss or gain of 1 cu yd (0.8 cu m) of material across the entire profile per foot of beachfront. The origin of this rule is obscure. It is probably based on a study of a portion of the North Carolina Coast (Jarrett 1977) in which measurements of shoreline advance and retreat data over a number of years were used. In order to convert this to a volumetric figure, Jarrett (1977) repeatedly surveyed two littoral profiles within his area of study from 1970 to 1974, comparing the actual measured volume changes associated with concurrent shoreline movements. He found that at these profiles, 1 ft (0.3 m) of shoreline advance or retreat was equivalent to 1 cu yd (0.8 cu m) of loss or gain of material along the entire profile per each lineal foot of beach. Although this value is probably a reasonably good average, it may not be valid for widespread use and was not so intended by Jarrett because of the observed differences in profile characteristics and closure depths from place to place.

The selection of a volume-equivalent factor for each study area, determined by monitoring a few select profiles, would be of substantial value in arriving at a local equivalence factor for the study area. This requires sufficient time of monitoring to observe changes of shoreline position, even if only in response to seasonal cycles. Another approach is to use wave data to obtain the best approximation of closure depth. This depth is added to the measured height of the beach from the low-water datum to the dune base. These data are used in computing a volume loss or gain assuming uniform retreat or advance by the method described in the *Shore Protection Manual* (SPM 1984), where the volume loss or gain is equivalent to

$$V = h\Delta x \tag{3}$$

where

V = volume of sediment gained or lost per unit length of beach front, ft^3/ft, m^3/m

h = vertical distance between dune and closure depth, ft, m

Δx = shoreline retreat or advance, ft, m

For example, if Δx were 5 m and h were 9 m, the entire volume gained or lost would be 45 cu m per meter of beachfront. The assumption of uniform retreat in most cases is probably not correct, as many repetitive profiles show that the retreat is not the same for the entire profile and is likely to be considerably less as one approaches closure depth. For this reason, the ability to monitor even a small number of profiles in the study area is valuable in providing more accurate measures of the actual volumetric loss across the entire profile per unit displacement of the shoreline.

Repetitive Littoral Profiles

A detailed and accurate method for measuring gains and losses of sediment along a given segment of shore is the repeated survey of established shore-perpendicular transects across the littoral zone. Direct measurement of the profiles provides a means of directly measuring the differences that occur in terms of volume gained or lost between the surveys. Chief disadvantages are high costs for field surveys and the extended length of time needed to collect data representative of not only seasonal changes but records of less frequent events that can have a large impact on the development of the shore segment under study. In many cases, the amount of money available to carry out the study or the lead time available for a project precludes a lengthy period of observation, making it necessary to use other methods. Even in this event, however, it would be valuable to monitor a small number of profiles for whatever period of time is available to better define closure depth, volume changes versus shoreline movements, and seasonal patterns.

Procedure

Littoral profiles are usually run perpendicular to the shore beginning at, or somewhat inland of, the coastline. They extend seaward to a short distance seaward of the closure depth. Initially, closure depths can be calculated from wave data (Hallermeier 1977, 1978, 1981; Birkemeier 1985) as discussed in Part I: Sediment Budget Boundaries. The profile lines are connected to a common baseline that extends in a shore-parallel alignment at, or inland of, the coastline. The spacing of profile lines need not be at regular intervals; narrower spacing may be required to cover places with complex geometry and

sediment distribution. Areas with more homogeneous geometry and sediment distribution require fewer lines. Profile lines are not confined to the beach. In most cases, profiles are carried seaward over the shoreface and are matched with the onshore lines. The transfer of lines through the surf zone and onto the beach is difficult at best because breakers and longshore currents close inshore can create special difficulties in obtaining precise configuration and elevation parameters for these zones.

Methods

In recent years, development of new and improved equipment and methods for survey control and offshore depth measurements has substantially improved the accuracy and efficiency of profiling shore and littoral zone configuration. The technology for land surveying is advanced, and highly accurate surveys can be made of beach and dune areas by standard methods. Extension of the profile lines seaward to the closure depth or toe of the shoreface is more difficult, especially in the breaker zone, but with care and proper equipment, accurate results can be achieved. Four methods of surveying offshore profile segments were tested comparatively in the field by the CERC in 1984, and reported Clausner, Birkemeier, and Clark (1986). Three of these systems currently in use and their operating characteristics are presented here. Not all methods were covered, but tests were run on the most common techniques in present use.

Fathometer surveys. Over the past few decades, the most common technique for surveying offshore profile segments has been to use an acoustic recording fathometer on a survey boat. Modern fathometers have high resolution and are reliable for use in any environment except the turbulent surf zone, where air bubbles in the water absorb the signal. Thus, an alternate means of connecting the offshore profile with the onshore portion is usually needed. The greatest advantages of modern echosounders are that (a) they can survey profiles faster than other methods and (b) they provide a continuous line profile reflecting small changes in bottom configuration.

Because the fathometer lines cannot be run inshore of the safe operating depth of the survey vessel, the gap between the onshore and offshore profile line segments can be relatively large. In this respect, amphibious vehicles that can come ashore and turn on the beach generally provide the best carriers for fathometer surveys (Bascom 1964). In addition, amphibians do not require harbor facilities, which can be a considerable benefit in reducing the time that is lost in transit to and from the work site. Because the fathometer is mounted on a floating platform, water depths must be corrected for water level fluctuations due to tide, wind, or wave setup, and for wave motion. Accurate horizontal control is provided by microwave positioning systems, which can make fixes at a rapid rate for completing the profile line.

CRAB. A unique system of obtaining profiles by using a self-propelled offshore vehicle was designed and built by the U.S. Army Engineer District,

Wilmington, in 1980 (Figure 13). It has been in use since then. It is called the Coastal Research Amphibious Buggy (CRAB) and consists of a 35-ft-high (10.7-m-high) aluminum tripod structure that is propelled by hydraulically powered wheels at the three corners of the tripod base. It carries a driver on an upper deck structure, and can be driven across the beach and surf zone into 30-ft (9.1-m) water depths. The position of the CRAB and the elevation of the rear wheels are determined at frequent intervals by use of a Zeise Elta-2 electronic total station aimed at a reflecting prism mounted a known distance above the rear wheel. One of the main advantages of the CRAB is that it rests on the ocean bottom; thus, elevations read from shore are independent of tidal or nontidal sea level fluctuations and wave motion. It is normally kept at the CERC Field Research Facility (FRF) in Duck, NC, where it is used for research projects and long-term repetitive profiling to measure bottom changes over time. Although it has been used elsewhere, it is difficult and expensive to transport and it is best used at fixed facilities such as the one at Duck, NC.

Sea sled. The sea sled is a simple construction, usually consisting of two metal runners connected by framing, that can be towed or winched along the seafloor (Figure 14). Most sea sleds are used primarily for survey purposes and thus carry a tall mast that can be used as a stadia rod or as a mount for a prism cluster to use with an electronic total station. Although various designs and dimensions are used, the sea sled is a simple and relatively economic means of obtaining high-accuracy profile data. Like the CRAB, the sled rests on the bottom and elevations measured are independent of fluctuations in sea level and waves. When used as a survey vehicle, the sea sled is usually towed behind a suitable boat or amphibious vehicle along the profile line, stopping at each survey station a sufficient time to allow the position and elevation to be determined. The accuracy and repeatability of sea sled surveys are comparable to those obtained by the CRAB. The sea sled has the additional advantage that it can readily be transported to different areas, since it can be broken down into a number of individual elements for shipment and can be readily reassembled at work sites. Because of the length of the runners, the sea sled does not provide good definition of relatively small bottom features. The sled at CERC's FRF, which has a 35-ft aluminum mast, can be used in water depths of about 25-30 ft.

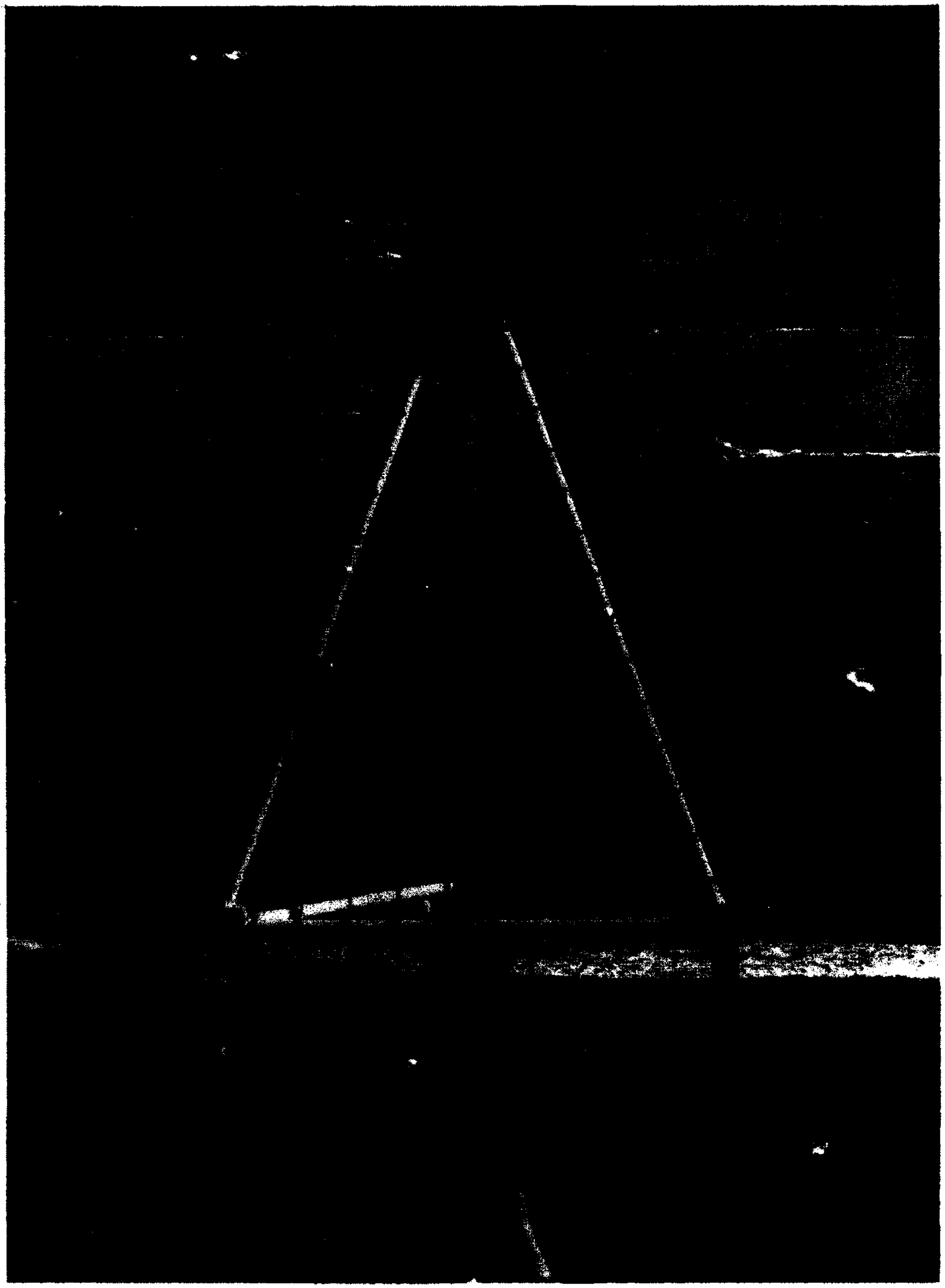

Figure 13. View of the Coastal Research Amphibious Buggy (CRAB) crossing a beach. The vehicle can be driven offshore to depths of approximately 9.2 m (30 ft)

Figure 14. Sled used at CERC's Field Research Facility with LARC amphibious vehicle

4 Sediment Source Analysis

Sediments are made up of particles of inorganic and organic material ranging from clay to boulder sizes (Table 6). Most sediments are produced by weathering and disaggregation of rocks. Initially these sediments may remain in place as residual deposits, but many are eventually eroded and moved from the place of their origin. Some sediments are moved great distances from the source and deposited in completely different environments. Such detrital (transported) grains are usually the main ingredients of shoreface, beach, dune, and back-barrier deposits. These deposits also normally contain various amounts of the hard parts of marine animals or plants that live in or have been transported into the area as detrital particles.

Most organic particles in coastal areas are produced in the submerged and intertidal zones, and are composed of calcium carbonate. Mollusk shells are usually the predominant organic material but many other types of organisms such as barnacles, bryozoa, calcareous algae, coral, and echinoids often occur as well. Many particles of organic origin, particulary coral fragments, are initially sand size but soon become fragmented into sand-size material in the high-energy environment of the beach and surf zone.

In addition to organic particles, some sediments contain authigenic particles that are created by direct precipitation of inorganic minerals or alteration of other minerals. Common authigenic components are various iron minerals, calcium carbonate, glauconite, and phosphatic grains. They may be either in situ or occur as detrital materials that have been transported from their place of origin. In tropical settings, especially where inorganic detrital sediment particles are scarce or absent, coastal deposits may consist largely or completely of organic and/or authigenic components.

Process and Response

In the process of erosion, transport, and/or extended periods of burial in intermediate sediment deposits, chemical and mechanical processes cause changes in the properties of sediment grains, both individually and collectively. There are three chief processes for these changes. First, sediment grains can be altered in size, shape, and surface texture during

Table 6
Sediment Classification

Unified Soils Classification	ASTM Mesh No.*	MM size	PHI Size	Wentworth Classification	
		4096.00	-12.0		
		1024.00	-10.0	Boulder	
		256.00	-8.0		G
Cobble		128.00	-7.0		
		107.64	-6.75	Cobble	
		90.51	-6.5		
		76.00	-6.25		R
		64.00	-6.0		
		58.82	-5.75		
		45.26	-5.5		
Coarse Gravel		38.00	-5.25		A
		32.00	-5.0		
		26.91	-4.75		
		22.63	-4.5		
		19.00	-4.25	Pebble	V
		16.00	-4.0		
		13.45	-3.75		
		11.31	-3.5		
Fine Gravel		9.51	-3.25		E
	2.5	8.00	-3.0		
	3	6.73	-2.75		
	3.5	5.66	-2.5		
	4	4.76	-2.25		L
	5	4.00	-2.0		
	6	3.36	-1.75		
Coarse Sand	7	2.85	-1.5	Granule	
	8	2.35	-1.25		
	10	2.00	-1.0		
	12	1.68	-0.75		
	14	1.41	-0.5	Very Coarse	
	16	1.19	-0.25		S
Medium Sand	18	1.00	0.0		
	20	0.84	0.25		
	25	0.71	0.5	Coarse	
	30	0.59	0.75		A
	35	0.50	1.0		
	40	0.42	1.25		
	45	0.35	1.5	Medium	
	50	0.30	1.75		N
	60	0.25	2.0		
	70	0.210	2.25		
Fine Sand	80	0.177	2.5	Fine	
	100	0.149	2.75		D
	120	0.125	3.0		
	140	0.105	3.25		
	170	0.088	3.5	Very Fine	
	200	0.074	3.75		
	230	0.0625	4.0		
	270	0.053	4.25		
	325	0.044	4.5		M
Silt	400	0.037	4.75		
		0.031	5.0	Silt	
		0.0156	6.0		
		0.0078	7.0		U
		0.0039	8.0		
		0.0020	9.0		
Clay		0.00098	10.0	Clay	
		0.00049	11.0		D
		0.00024	12.0		
		0.00012	13.0	Colloid	
		0.00006	14.0		

* Mesh sieves seldom used for gravel larger than 8 mm diameter. Adapted from Hobson (1979) and other sources.

transport by collision with other grains or larger objects. These collisions result in grain fracturing and abrasion, thus often changing size, shape, and grain surface textures. Second, when buried for extended time (up to millions of years) in deposits in terrestrial environments, they undergo diagenetic changes by partial or complete dissolution of grains or by precipitation of overgrowth on grain surfaces, causing changes in size, roundness, and surface texture. The third process is known as selective or preferential sorting. This is due to the differences in response of different sediment grains to a flow of water or air in accordance with grain size, specific gravity, and grain shape. As a result, some grains move farther than others in equal flow conditions, leading to their spatial segregation and a tendency for grains of equal size, specific gravity, and shape to become associated. However, other factors such as uneven and highly variable flow conditions, mixing with other sediments, chemical interactions, bioturbation and other biological effects, and the effects of bed forms often prevent the sorting process from achieving well-developed sorting.

Sediment Sources and Transport Routes

Analyses of selected coastal sediment samples is undertaken for a variety of reasons. Examples include investigation of engineering properties for construction design, prediction of sediment erosion or accretion under certain circumstances, selecting sand borrow sources for beach fill projects, and identification of the sources and transport paths of sediments found in coastal deposits. In terms of sediment budget studies, the last factor is the most important. This importance lies in its relationship to maintaining a flow of sediment to beach and littoral areas to achieve dynamic balance with losses. Any interruption of this process of supply by man-made engineering works, or long-term trends in natural processes, is a potential cause of beach erosion which leads to subsequent loss of recreational resources and protective beaches and dunes that diminish storm damage to the coastal area. Examples are the damming or diversion of fluvial sources of sediment supply, interruption of littoral drift by the opening of inlets, construction of jetties or breakwaters that trap sand, or the building of seawalls and bulkheads against cliffs that act as a source of sediment to downdrift beaches.

Sediment sources are usually classed as ultimate (or primary) sources and immediate (or proximate) sources. Between its journey from the ultimate source to the immediate source, the transport can be interrupted repeatedly by burial in sediment deposits. This may be for only a short period of time as a consequence of short-term seasonal or other factors. In many cases, especially in coastal plain areas, grains may remain lodged in a deposit for many millions of years before changing geological conditions result in their re-erosion and continuation of transport to the coast. These can be considered as intermediate (or secondary) sources. When ancient rocks or sediments occur within a littoral compartment where they are eroded and added to the

active sediment mass, they are both ultimate and immediate sources. Together with organic and authigenic material produced within the boundaries of a littoral compartment, they can be considered internal sources. Another type of internal sediment is derived from retreating barriers by the outcrop of dune, overwash and lagoonal sediments being overridden by the barrier and exposed (usually on the lower foreshore and upper shoreface). The sediments are then eroded and added to the active littoral sediment (Figure 9). The dune and overwash sediments having once been on the beach can be considered recycled sediments. Lagoonal sediments are primarily fine-grained sand, silt, and clay that accumulated in the low-energy back-barrier area. In most cases they are not stable in a beach environment, and contribute little to the active littoral sediment supply. Lagoonal elements on beaches are often indicated by shells of lagoonal organisms, in particular the oyster *Crassostrea virginica*, and by marsh peat washed up on the beach or exposed in the lower beach.

Techniques now available for tracing sediments along transport routes and locating source areas by comparative analysis of various characteristics of the sediment in terms of both individual grain characteristics such as mineralogy and collective properties such as grain size distribution will now be presented. Some promising methods are of relatively recent origin and have not been used a sufficient length of time to be reliably assessed for general application. In general, the best methods of study are different from place to place, and it is desirable to have a variety of techniques available so that one or more can be effectively used in any given area.

Coarse Fraction Analysis

Many approaches to the study of sediment constituents have been developed over the years to obtain information about the origin, history, and stratigraphic relationships of sediment deposits. Most such techniques are concerned with one or two components such as size frequency distribution or heavy minerals. Shepard and Moore (1954) stated that it was unfortunate that only limited use was made of the many aspects of sediment characteristics because they contained potentially valuable information. They described a more comprehensive approach to analyzing sediments which they called coarse fraction analysis (further described by Shepard (1973)). Ingrim (1965) described a similar procedure to identify and describe sediment units for facies mapping. He listed the basic equipment needed and provided comparison charts for rapid quantitative estimates of various factors.

Basically, coarse fraction analysis utilizes the sand-size and larger components of sediment samples. Fines (silt and clay), if present, are removed by washing the samples in a sieve having a 63-micron screen (U.S. Standard Sieve No. 230). Cleaned samples are then examined under a binocular microscope and described in terms of such features as grain color, recognizable grain mineralogy, biogenic content (if present), grain shape, and

any other aspects that are characteristic and can be used for comparative analyses with other samples. Because some factors such as grain shape are affected by grain size, it is usual to separate the sample into size fractions for analysis.

Shepard (1973) points out that coarse fraction analysis is not a highly accurate technique but uses a comprehensive approach to sediment analysis that provides useful results in most cases. Coarse fraction analysis seems especially well-suited as a rapid and economical means for initial processing of a large number of samples to gain some insight into the information they contain, and to select typical samples and methods of analysis for more detailed study (Ingrim 1965).

Grain Size Distribution

The environmental implications of sediment grain size distribution have been the subject of many studies. These studies were motivated, in most cases, by a need to find ways to identify the environment of deposition from small drill-hole or subaqueous samples where the only information available was what could be learned from the sample itself. Methods of analyzing sediment size generally make use of the size-frequency distribution and, in particular, certain statistical measurements that relate to the nature of the size distribution curve. The main measures are the mean and median size, standard deviation, skewness, and kurtosis.

In the context of this report, the interest in environmental interpretation is whether the size distribution can be used as an indicator of sediment sources because sediments acquire characteristics related to the specific type of environment from which they came before entering the coastal compartment under study. This seems unlikely because sediment size characteristics are easily altered by selective sorting and tend to rapidly adjust to any new situation during the course of transport. Thus the environmental "signature" acquired from sediment size distribution in one environment is not likely to be retained in any other environment to which the sediment is transported. Environmentally conditioned size distribution patterns are retained mostly in situations where the environment of an area changes and the older sediments have been isolated from rearrangement by lithification or burial.

In recent years the value of size-frequency distribution as an environmental indicator has been questioned (Shelley 1985, Boggs 1987). Limitations of available sediment grain sizes, mixing of sediments from two or more sources, and the rapid adjustment to time-variable energy conditions are among the reasons that the procedure has been questioned.

At present, it seems that sediment grain traits other than size distribution (e.g., composition, shape, and grain surface texture) are likely to be more

useful as source indicators, although in some circumstances size distribution may be of value in eliminating possible sources because of overall grain size. For example, an eroding cliff of sediments finer than those found on an adjacent beach cannot be the source of the beach deposits.

Grain Surface Texture

The surfaces of sand grains are often marked by pits, scratches, overgrowths, and other features that are related to their history. Such marks are made by grain collision, sliding, gouging, dissolution, overgrowths, and other incidents that have occurred during the grains' existence. Although the presence of surface marks was long known in a general way (for instance, the distinction between clear and frosted grains) the markings were not investigated in detail until relatively recent times. With the advent of the electron microscope in the early 1960s, it became possible to obtain the high magnification, good resolution, and depth of field needed to detail surface marks. Important early works appeared in 1962 (Biederman 1962, Porter 1962, Krinsley and Takahashi 1962). Since then, many studies have been published concerning the interpretation of environmentally significant grain surface textures. Although primarily a means of discerning depositional environments, the presence of unique surface markings that are not related to the environment in which the sample was collected have potential tracer value. For example, a sand grain collected from a beach area may contain markings characteristic of a fluvial, glacial, or some other former environment that is evidence of earlier sources and transport paths.

Surface texture studies are normally performed on quartz grains because they are widely available on temperate coasts, and have sufficient mechanical and chemical resistence to preserve evidence of former environments. Interpretations are made visually from scanning electron microscope (SEM) images. Measurements, frequency counts, and statistical analysis have not been tested to any great extent at the present time but many prove valuable in the future.

The variety of features recognizable on quartz grain surfaces are numerous. As research continues in this active field, increasing comprehension of the meaning of these features in terms of environment and provenance should be realized. One of the main difficulties with surface texture analysis is that it requires expensive equipment and trained technicians to obtain SEM images suitable for deciphering grain surface texture. The analysis of sufficient numbers of grains per sample (28 to 30) generally requires a full 8-hr workday (Krinsley and Marshall 1987). In addition, relatively few geologists have extensive experience in interpreting the textural patterns. However, it is a promising procedure that may be of increasing significance in sediment budget studies in the future.

Biogenic Tracers

Sediments often contain particles derived from living organisms. In many cases these particles are useful natural tracers because they either (a) are found in an environment outside their natural habitat (exotic), or (b) are extinct types that have been eroded from ancient sediments or rocks.

On many beaches, the most conspicuous biogenic elements are the shells of mollusks. Common among them in many areas are bivalves of the genus *Donax*, a type adapted to life in the lower beach and adjacent high-energy surf zone. Apart from *Donax* most other mollusks found on beaches are adapted to life in the permanently submerged waters seaward of the low tide level. Their presence on the beach is a result of onshore transport by waves. Some species such as *Mulinia lateralis* and *Anadara ovalis* (Bruquiere) are quite common on beaches, probably because their inshore range limit is near the shore. On many barriers, mollusk shells adapted to the back-barrier lagoon, marsh, tidal creek environment, especially the oyster *Crassostrea virginica*, are evidence of retreat of the barrier over its own back-barrier deposits.

Many other remains of subtidal organisms can be found on beaches, especially those that are easily transported (e.g., sponges, echinoids, and marine algae). Other exotic organic detritus on beaches include pieces of worm reef, barnacles, peat fragments, hard and soft corals, univalve mollusks, and many other types of marine plants and animals living seaward of the low-water line.

In addition to macroorganisms, certain shelled microorganisms occur in beaches. Because of the high energy at many beaches, shells of these small organisms probably have a relatively brief existence and most are soon destroyed. Thus at high- and moderate-energy beaches they are probably being replaced on a continuing basis. At low-energy beaches or during prolonged periods of low wave energy, their number is usually much increased. The microorganisms most often occurring are specimens of formanifera and ostracods, especially the former. Like other marine organisms, the formanifera and ostracods have a finite range usually recorded in terms of water depth. However, the lack of detailed studies on distribution makes this a very uncertain guide in most places.

Heavy Mineral Analysis

A limited form of coarse fraction analysis that has long been used by geologists for study of rocks and sediments is heavy mineral analysis. Often in the past, heavy mineral studies focused on the presence of minerals with economic value (limonite, monazite, or zircon). However, heavy minerals

also have been used as potential natural tracers showing the sources and transport paths of material in coastal and fluvial sediment deposits.

Heavy mineral analysis is performed using an apparatus that allows the heavy minerals to be recovered (Carver 1971). Mineral species having a specific gravity (SG) greater than bromoform (SG 2.87) or a similar heavy liquid are classed as heavy minerals.

Heavy minerals in beach deposits have been investigated by many researchers interested in their tracer value (Martens 1935; McMaster 1954; Hsu 1960; Guy 1964; Giles and Pilkey 1965; Neiheisel 1965; Judge 1970; Swift, Dill, and McHone 1971; Luepke 1980; Meisburger 1990). In general, most heavy mineral studies have led to conclusions on a regional scale rather than the more localized patterns that are of most significance in sediment budget analysis. One of the chief difficulties is that during transport or reworking, the difference in specific gravity between the heavy minerals causes selective sorting that can drastically change the frequency distribution. Because of this, it is usually impossible to make any reliable conclusions about sources based only on heavy mineral species frequency distribution. One must often try to isolate some varietal differences in the same mineral species that may give results independent of specific gravity differences (Folk 1968). In regions where there are complex lithologies, well-separated drainage systems, and littoral compartments (much of the California coast), the use of heavy minerals is most often practical because one or more minerals may be unique to a specific source or drainage system. In contrast, beaches that front large coastal plains typically have a limited heavy mineral suite that consists mainly of the more common mineral species that are hard and stable enough to survive long transportation and long weathering in intermediate coastal plain deposits. Often the channel shifting and the reduction or elimination of softer and more unstable minerals leads to similarities of heavy mineral suites over a considerable extent of coast.

Particle Shape Analysis

Each sediment particle has a unique shape that reflects the original grain morphology and subsequent modifications caused by chemical and mechanical processes. Detrital sediment grains thus carry information about their ultimate source and post-erosional history of transport and weathering. Efforts to classify and interpret grain morphologies (Wentworth 1919, Wadell 1932) were concerned mainly with classification of their roundness and sphericity by dimensional measurements or by comparison to graphic images of a series of grains, ranging from very angular to well rounded morphologies (Powers 1953, Shepard and Young 1961). In the past two decades, grain shape analysis techniques have been improved in detail and objectivity by using computer-assisted electronic methods of characterizing grain shape.

Detrital particles owe their shape characteristics to their original form and the effects of chemical and mechanical processes that occur during weathering and transportation. These processes, in turn, are influenced by the hardness and chemical stability of the particle, mode and distance of transport, grain size, and weathering during any extended periods of deposition interrupting the coastward journey. To minimize variables, it is customary to analyze grain shape of a single mineral species and size class. The preferred mineral for this is quartz (SG 2.66; hardness 7) because it is usually the most abundant mineral in sand deposits.

The shape of a sediment particle can be partly described by two qualities (roundness and sphericity), and many classification schemes are based on these properties. Roundness is a measure of the extent of rounding of sharp edges. Sphericity is a measure of the overall form with respect to a sphere. Geometrically, roundness and sphericity are independent variables. Rounding of a quartz grain is most likely to occur by way of three processes. One of these is mechanical, the slow grinding that occurs in transport as a result of abrasion and collision with other particles. Other causes of rounding are of a chemical nature and consist of dissolution and/or the formation of overgrowths on the grain surface. These most often occur during periods of deposition that may last up to millions of years before changing geological conditions result in re-erosion and renewed transport.

Effects of grain size

The effects of grain size on the roundness of sediment grains are significant when roundness is due to mechanical attrition. Twenhofel (1945) found that particles smaller than 0.250 mm were little affected by mechanical wear, especially in a subaqueous environment. Kuenen (1960), based on experimental findings, concluded that eolian transport was much more efficient in creating roundness than transport by water. Thus, with increasing grain size, abrasion seems to also increase because of greater particle mass. Ehrlich et al. (1980), using data from Fourier grain shape analysis (described later in this document), concluded that a relationship existed between grain size and shape that had to be considered in sample analysis.

Many studies of roundness and sphericity made on gravel-sized sediment indicate that gravels are likely to undergo shape changes at a much more rapid rate than sand-sized material. In general, gravel-sized material is easier to measure and classify than sand-sized material. In addition, gravel is more easily "tagged" for tracer studies than sand, and is easier to follow as it moves. Many such studies have been made on material in glaciated regions such as England where gravel is often an important part of the beach sediments, or on highland coasts where fluvial transport from sources to the coast is relatively short and rapid. In the United States, most gravel shore deposits occur in New England and on parts of the Pacific coast. The majority of beach deposits elsewhere in the United States are predominantly sand.

In addition to the effects of grain size, the frequency distribution of roundness and sphericity in a given deposit may show effects of selective sorting by size and/or shape. Sorting by size is characteristic of all sediment transport because the finer grains tend to be carried farther than coarser particles once moving in a current. For comparative studies it is therefore customary to examine shape characteristics for a limited size range within the samples rather than examining whole samples. Some studies have focused on a specific size range; others may cover a series of sized samples separated from the same sample by sieving. In addition, a mineral's specific gravity is an important aspect of sorting, because the denser minerals of a given size will tend to lag behind the less dense minerals during transport (the lighter particle is more readily transported). Consequently, it is customary in shape analysis to work with a single mineral species, usually quartz (SG 2.66, hardness 7). This is usually the most abundant mineral in sedimentary sand deposits.

Effects of grain shape

Grain shape itself may be a cause of sorting. Evidence of this is apparent in many comparative studies of grain shape in beach and adjacent coastal dune sands where the frequency of rounded grains is higher in the dunes than on the beach. This is sometimes attributed to the greater attrition potential of eolian transport. However, because of the episodic nature of wind transport and the short travel distance involved, this is questionable. Shepard and Young (1961) suggest that the differences may be due to selective sorting processes in which the rounder grains are preferentially selected for wind transport to the dune area.

Visual shape analysis

The most economical and rapid method of grain shape analysis is by microscopic inspection of a sample of sediment and comparison to graphic representations (drawings or microphotographs) representing a graduated series of two-dimensional shape characteristics from very angular to well-rounded forms (Krumbein and Sloss 1951, Powers 1953, Shepard and Young 1961). In practice the analyst views a selected number of grains split from a sample and compares each with a graphic grain shape scale to classify the shape characteristics. In general, the photographic scales are most useful because of their greater detail and because they provide some information on the third dimension (Shepard 1973).

The chief drawback to visual shape classifications is that the number of categories creates a series of gray areas in which classification is uncertain. Thus, subjectivity is a significant factor in causing differences in classification between different classifiers or the same classifier at different times. However, the method is reasonably accurate where strong shape contrasts exist. Clemens and Komar (1988) provide a recent example. A less complex use of visual classification employed by many researchers uses only two

classifications, angular and rounded (Carver 1971). This leaves only one gray area, and is relatively objective.

Dimensional Analysis

Measurement of primary axes of sediment grains has been used to obtain parameters such as length-width relationships as a means of classifying grain shape (Wentworth 1919, Wadell 1932). These methods are relatively slow and tedious with sand-sized material, and have probably been used more with gravels and coarser detritus. Much more detailed and rapid descriptions of grain sand size shape are now possible by using modern electronic imaging and calculating capabilities. Of these, the earliest to be developed is Fourier grain shape analysis (Schwarcz and Shane 1969, Ehrlich and Weinberg 1970). Automated scanning systems for obtaining data on each grain are now available, and greatly reduce the time necessary to classify a sufficient number of grains from a sample to be representative. An alternate method of indexing shape, presented by Orford and Whalley (1987), makes use of the fractal dimension technique of Mandelbrot (1977), and is more suited to dealing with highly irregular shapes.

Fourier Grain Shape Analysis

A little over two decades ago, a method of quantitively describing the maximum projected two-dimensional outline of a particle by a Fourier series in closed form was described by Schwarcz and Shane (1969) and Erlich and Weinberg (1970). Rather than describing shape in terms of only two variables (roundness and sphericity), Fourier analysis allows compartmentalizing the maximum projected profile of a particle into a series of standard shape components known as harmonics. The contribution of a harmonic to the shape is known as harmonic amplitude. It has been found that for detrital quartz particles, sufficient information is contained in the first 20 harmonics to closely reproduce the original shape (Ehrlich et al. 1980). When a representative number of grains are analyzed (usually 200-400) the shape-frequency distribution can be characterized for each harmonic by a histogram plotting harmonic amplitude classes against frequency of occurrence. Comparative study of these data can be made by visual or numerical means to evaluate the form relationship or lack of relationship (correlation) between samples. A complex mix of multisource sediments also can be "unmixed" by the analysis into separate types related to source and history.

Causes of shape differences

Grain shape is related to the circumstances of origin, and the results of abrasion and weathering that occur in transport and during periods of deposition in intermediate sources. The abrasion of sand grains tends to reduce the finer irregularities of grain outline, and to ultimately produce a relatively smooth outline compared to the original shape of many grains at the source. In addition, partial dissolution and/or accretion of overgrowths also can change the grain shape of sediment when it is buried in an intermediate source for a length of time. However, even highly abraded sand particles were found by Mazziullo (1987) to retain distinctive shape characteristics acquired at their ultimate source. These characteristics are most apparent in the lower harmonics, which depict gross shape, while abrasion effects tend to reduce small irregularities in the outline that, if present, are most clearly depicted by the higher harmonics.

Selective sorting

A very important aspect of grain shape analysis is that it can be used on single mineral species. This virtually eliminates selective sorting by specific gravity that takes place with mixed mineral assemblages. Size sorting also can be minimized by working with a relatively narrow size range. Because of its usual abundance in sand and silt, quartz is the mineral most often used in grain shape studies. Few other mineral species have been investigated, but most also would be satisfactory for Fourier grain shape analysis if sufficiently abundant. Katz and Pilkey (1987) used mica as the moneral species for grain shape study.

Data acquisition

Because of the large number of grains per sample needed for representative analysis, making necessary measurements by hand is impractical if any but a small number of samples are needed. The use of electronic methods for data acquisition and subsequent processing is more efficient, and studies can be made at a reasonable cost in time and resources. Telford et al. (1987) describe a relatively economical video imaging system that can automatically scan and digitize the grain boundary for data input to the Fourier analysis.

Present status

A literature search for publications concerning Fourier grain shape analysis in March 1992 listed 21 journal papers, 18 abstracts, 10 M.S. theses, and 5 Ph.D. dissertations. A substantial amount of the sources found were produced by faculty members and students of the University of South Carolina and the University of Southern California. These publications provide

considerable information about techniques, and a number of applied studies addressing practical problems also are included.

Presently a definitive assessment of this technique is not possible because of the paucity of controlled studies of sediment sources and transport paths that have been developed by other methods. Those that have been augmented by other evidence have indicated that the method is viable and can be applied with good results to many sediment budget studies (Osborne, Yeh, and Lu 1991). The technology for analyzing sediment grain shape distribution for the basic data has been well-developed and future work will probably add additional improvements in technique. The main need at present is additional applied studies in a number of locations where information has been or can be obtained by other methods as well. Fourier grain shape analysis appears to be a viable procedure in concept and technology that has the potential to be an important aspect of sediment budget studies in many, if not most, areas.

5 Summary

Sediment budgets are a means of accounting for the supply and loss of sediment, through time, in a designated area. Sediment budgets of coastal areas are used to estimate the gain and loss of littoral sediments in one or more contiguous sections of coast. These studies are important in the planning and design of coastal engineering works and in the management of coastal resources. Sediment budget studies involve two major operations; (a) identification of potential sediment sources and sinks for each littoral compartment of the study area, and (b) estimation of the rate of sediment gain or loss in each of these littoral compartments. In many cases some potential sources or sinks are apparent from analysis of the general morphology and drainage patterns of the coastal area under investigation. Other sources may not be as apparent and can only be identified, if at all, by a more detailed comparative study of sediment composition and grain characteristics to identify natural tracers. Estimating the rate of sediment gain or loss, once sources are identified, can be a difficult process and results vary in their reliability. The technique most often used for quantitative studies involves the estimation of longshore drift rates on the basis of an analysis of historical weather data. This is accomplished by a sequence of operations involving estimation of deep-water wave climate affecting the study area, transformation of the deep-water waves to site-specific shallow water wave and breaker characteristics, calculation of the longshore energy component of the breaking waves, and determination of direction and rate of longshore sediment drift associated with the wave energy flux. In this process, each step is dependent on the accuracy of the preceding steps and on the validity of the models used.

Deep-water wave gaging data now being collected off the United States coasts will provide deep-water wave climatology of greater accuracy than can be obtained by hindcasting, albeit hindcasting will still remain valuable because of the wide coverage and long extent (history) of marine weather data. Shallow-water wave gage data in coverage areas will allow bypassing deep-water wave statistics and shallow-water transformation procedures. It is significant that wave gage data can be used to good advantage as ground truth in research efforts to improve existing methods and models for wave hindcasting, forecasting, and shallow-water transformation procedures.

Measurement of long-term trends in shore position can be made using historical maps and chart data covering the study area. In many areas of the

United States, early surveys were made more than 150 years ago, and subsequent surveys to update the data often have been made several times in later years. Comparison of shoreline positions for a historical series of maps or charts can be used to measure changes in shoreline position through time and determine whether the shore has been more or less stable, fluctuating in an irregular fashion, or moving in a consistent trend. The conversion of shoreline movement to quantitative volumetric estimates of gain or loss in sediments is inexact. Usually conversion is made by a rule-of-thumb relating shoreline movement to gain or loss of sediment across the entire profile. Similar shoreline movement studies using aerial photography also are valuable, but the time range of available photography does not extend more than about 60 years.

The most accurate means of calculating gain and loss of sediment is the monitoring of beach and shoreface profiles over a period of time. The expense of long-term profiling studies is high, and the amount of time available for such studies is usually limited because of project schedules. However, even short-term profile studies are valuable to define seasonal patterns, closure depth, and the relationship of shoreline movement to volume gain or loss across the profile to enhance shoreline movement data. Highly accurate methods for profile surveys, both on the shore and in the seaward submerged area, are available.

Sediment source information is often incomplete or deficient because of the difficulty of identifying all of the often multiple sources of beach sediment. Many methods of study, such as identifying heavy mineral assemblages, are of value in some areas but in other areas provide little direct value to working out sources and transport paths. This is especially true in coastal plain environments, like much of the Atlantic and Gulf coasts of the United States, where most heavy mineral studies have led to conclusions on a broad regional scale, rather than the more detailed and localized information needed to recognize immediate sources and transport paths. The use of varietal types of single mineral species is more likely to provide satisfactory natural tracers than the frequency distribution of the full mineral suite because of the effects of selective sorting on the frequency distribution characteristics (Folk 1968, Meisburger 1990). Study of particle shape, usually performed on the quartz fraction, is proving in many cases to be a sensitive indicator of previous environments, and has tracer value especially when shape distribution statistics are developed by methods such as Fourier grain shape and fractal shape analyses (described in Chapter 4 of this document).

The majority of beaches where sources have been studied have proven to be composed of material from more than one source. Mainland beaches, for example, can have significant contributions from substrate or cliff erosion, littoral drift, onshore transport, stream discharge, and organic or authigenic sources. Causes of sinks also can be multiple, with important losses to eolian transport, overwash deposition, littoral drift, inlets, submarine canyons, and offshore transport. It is doubtful at present that a full accounting of all sources and sinks can be made on most beaches because of the difficulty of

isolating and identifying material gained and lost to the various sources and sinks. However, in most places large-scale contributions and losses can usually be accounted for by detailed study. The greatest area of uncertainty is the role of onshore-offshore transport in sediment budgets. Many sediment budget studies have shown significant gains or losses to beaches that cannot be accounted for by other known sources. In many cases such gains have been attributed to onshore transport from the inner shelf area.

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Appendix A: Glossary

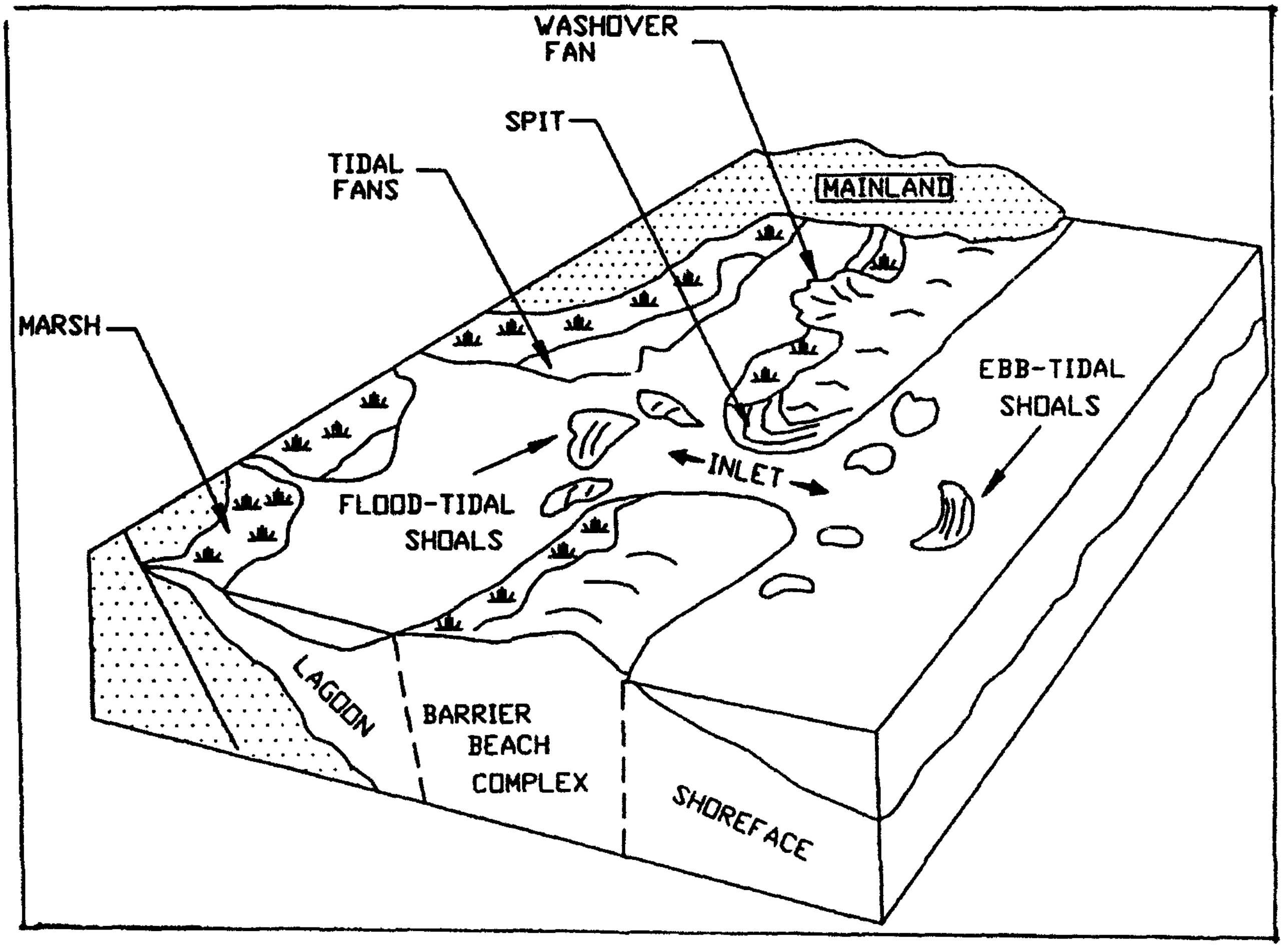

Figure A1. Barrier coast showing principal features

AEOLIAN (EOLIAN) Pertaining to the wind. In geology usually referring to wind-transported sediments.

AUTHIGENIC Formed or generated in place. Rock constituents or minerals that are found in the place where formed.

BACK BARRIER Pertaining to the lagoon-marsh-tidal creek complex in the lee of a coastal barrier island, barrier spit, or baymouth barrier (Figure A-1).

BARRIER, COASTAL Elongate, shore-parallel, usually sandy, features that front coasts in many places and are separated from the mainland by bodies of water of various sizes, and/or salt marshes, lagoons, mud, or sand flats, and tidal creeks (Figure A-1).

BEACH FILL A process of placing sand from an outside borrow source on beaches and dunes to restore or enlarge them. Also applied to the material so used.

BORROW A source of sand or gravel used to furnish material for beach fill or other engineering activities.

CLOSURE DEPTH The depth beyond which sediments are not normally affected by waves.

COASTAL COMPARTMENT A subdivision of a coastal area used to calculate sediment budgets. The boundaries of a coastal compartment can be arbitrary, but should, if possible, represent some natural subdivision.

COASTAL PLAIN A relatively low plain of subdued topography underlain by horizontal or gently sloping sedimentary strata extending inland of a coastline.

CONTINENTAL SHELF The submerged zone bordering a coast from the toe of the shoreface to the depth where there is a marked steepening of slope.

DETRITAL Having been transported to a place where found as opposed to in situ formation.

DIATOM An algae that is contained in a microscopic exoskeleton made of silicon dioxide.

DOWNDRIFT The direction in which littoral drift is moving.

FLUVIAL Pertaining to streams; e.g., fluvial sediments.

FRIABLE Weakly consolidated or weathered rock that is easily broken down.

GLAUCONITE An earthy, green amorphous mineral that forms in the marine environment.

GROIN A low, shore-normal, perpendicular structure erected on beaches to trap sand moving alongshore.

HEAVY MINERAL Mineral species with a specific gravity greater (usually 2.9 or higher) than a heavy liquid such as bromoform used to separate heavy minerals from lighter minerals.

INLET A connecting passage between two bodies of water (Figure A-1).

INTERTIDAL Between high and low water.

JETTY A shore-perpendicular structure built to stabilize an inlet and prevent the inlet channel from filling with sediment.

LAGOON Open water between a coastal barrier and the mainland. Also water bodies behind coral reefs and enclosed by atolls (Figure A-1).

LITHOLOGY The general character of a rock or sediment.

LITTORAL DRIFT The movement of sediment alongshore. Also the material being moved alongshore.

MARSH A permanently or periodically submerged low-lying area that is vegetated.

NATURAL TRACER A component of a sediment deposit that is unique to a particular source and can be used to identify the source and transport routes to a place of deposition.

OOLITE A rounded particle of calcium carbonate formed by precipitation from sea water as an authigenic mineral.

OVERGROWTH An authigenic mineral precipitated on a preexisting mineral grain.

OVERWASH A process in which waves penetrate inland of the beach. Particularly common on low barriers.

PHOSPHATIC GRAINS Sediment grains composed of phosphate minerals or rock fragments.

SELECTIVE SORTING A process occurring during sediment transport that tends to separate particles according to their size, density, and shape.

SHOREFACE A seaward-sloping ramp, seaward of the low-water line that leads to the inner continental shelf and is characteristically steeper than the shelf floor (Figure A-1).

SHORELINE The line of demarcation between a shore and the water. May fluctuate periodically due to tide or winds.

SINK A process that depletes sediment. Also the feature or area into which sediment is lost.

SOURCE A process that adds sediment to a deposit. Also the place from which the sediment comes.

SPIT An elongated, usually sandy, feature aligned parallel to the coast that terminates in open water (Figure A-1).

STRATIGRAPHY Study of stratified deposits or rocks.

SUBTIDAL Below the low-water datum; thus, permanently submerged.

TIDAL CREEK A creek draining back-barrier areas with a current generated by the rise and fall of the tide.

TIDAL SHOALS Shoals that accumulate near inlets due to the transport of sediments by tidal currents associated with the inlet (Figure A-1).

UPDRIFT The direction along a coast from which littoral drift material is moving.

WASHOVER Sediment deposited inland of a beach by overwash processes (Figure A-1).

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Sediment budget studies are of great importance in many coastal engineering projects. In general, a sediment budget is a compilation of the sources and amounts of sediment that are gained or lost in designated coastal reaches during a specific interval of time. Sediment supply for a given coastal area may be derived from several sources and may involve different means of transport. The analysis of sediment budgets includes the study of:

- the influence of waves on alongshore and onshore-offshore sediment movement.
- the effects of tidal and other coastal currents on sediment movement.
- sediment accretion rates at barriers and traps.
- historical shoreline changes.
- long-term measurements of littoral profiles.

Sediment sources and transport paths must be identified as part of the sediment budget process. In many cases, important sources are apparent from observation of the geomorphic aspects of the coastal terrain. Often,

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sources are obscure and study of much more complex aspects of the sediment, such as particle composition and shape characteristics, is needed. In many cases, existing methods are not sufficient for positive identification of all sources. Techniques for source identification and quantitative accounting of sediment supply and loss are important areas of continued research efforts to improve the methodology.